UNIVERSITÀ
DEGLI STUDI
DI PADOVA

UNIVERSITA’ DEGLI STUDI DI PADOVA

Dipartimento di Ingegneria Industriale DII

Corso di Laurea Magistrale in Ingegneria Energetica

The Adaptation of Energy Systems to Climate Change Scenarios

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Anno Accademico 2015/2016

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Master Degree in Energy Engineering

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Academic Year 2015/2016

There is a tall wall between our scientists and our decision makers. Scientists do their research and lob their information over the wall, hoping that somebody on the other side will catch it in receptive hands and act on it. However, what is on the other side of the wall is a big pile of papers and information that the decision makers pay no attention to

(Jonathan Foley, 2010)

TABLE OF CONTENTS

INTRODUCTION

> Warming of the climate system is unequivocal, and since the 1950s, many of the observed changes are unprecedented over decades to millennia. The atmosphere and ocean have warmed, the amounts of snow and ice have diminished, sea level has risen, and the concentrations of greenhouse gases have increased. (IPCC, 2013, p.4)

The Working Group I (WGI) of the Intergovernmental Panel on Climate Change (IPCC) in the Fifth Assessment Report (AR5) states the magnitude of the problem that our planet is suffering.
The climate is changing. It has especially mutated during the last sixty years, though this change started earlier. Deviations have been observed from the beginning of the 20th century. Even if we know the cause of all this – the excessive and incorrect use of energy resources by humankind to meet the increasing demand of energy – the most important aspect is that climate change is occurring, and its effects within the coming half century are partially inevitable. If we do not do anything to alleviate climate change, the consequences might be irreparable for the entire world.

In the last decades the question of climate change has become the focus of international concern. The international scientific community concluded that there are two main approaches to tackle climate change: mitigation and adaptation.
Mitigation and adaptation were too often considered as alternative options in the fight against the effects of climate change. Mitigation consists of limiting the process of future climate change in two ways. The first one is to reduce GHG emissions at the source (from the various economic sectors); the second is to develop sinks that can capture and hold GHG separately from the atmosphere. Adaptation, instead, is the process of adjustment to actual or expected climate and its effects, in order to either lessen or avoid harm or exploit beneficial opportunities (IPCC, 2015, p.118). Greenhouse gases have a long lifetime in the atmosphere and a certain inertia: thus, the effects of emissions are extended in time. Even if we stop GHG emissions immediately, those that have already been issued will still lead to climate changes. As we become aware of the difficulties of defining and obtaining mitigation objectives that are at the same time mutual, realistic and sufficiently ambitious, adaptation becomes fundamental to manage and prevent the inevitable.

Until now, most of the debate has been focused on the mitigation aspect. Though, in recent time, mostly because of the aforementioned recognition that climate change can not be avoided, the adaptation of energy systems has become increasingly relevant and also, by all accounts, the best way to deal with climate change.

The topic of this thesis is the study of the prospects for adaptation to climate change of energy systems, and especially of the electricity one. Energy demand (that is continuously increasing) can not be met without the use of the actual energy system. The supply of energy by means of current energy systems, and the consumption of energy resources especially non-renewable, have ensured the contamination of natural systems and the change of the climate system. However, we have to reckon that there is a strong vice-versa relationship between energy systems and climate change. The energy generation cause changes on climate: it is also true that climate change affects all that is related to energy usage and production. In this sense, the concept of adaptation of energy systems to climate change becomes increasingly fundamental. It should be the basis for establishing new energy policies, to supply energy demand, to preserve energy infrastructures and therefore make the system resilient to climate change.

Not introducing promptly appropriate actions in order to adapt energy systems, the cost of system management, energy production and reduction of climate change's impacts will become higher and higher. In the report *Global landscape of climate finance 2015* of the Climate Policy Initiative, the authors declared that adaptation finance reached $25 billion in 2014 (Buchner et al., 2015, p.9). But there is the need to do more. In agreement with *Global Landscape of Climate Finance* (2015, n.d.), $13.5 trillion is the investment required over the next 15 years in energy efficiency and low-carbon technologies to implement the national climate pledges (the so-called "Nationally Determined Contributions") that countries made before the international climate negotiations which will hold in Paris in December 2015. With $13.5 trillion pledged, we will make significant progress, but we will not be able to limit the global temperature increase to 2°C. The investment required over the next 15 years should be $16.5 trillion.

As said before, up to present time, mitigation has been the most studied approach. But something has already been done in the adaptation direction.

The IPCC is the benchmark. Most of the studies in literature refer to the various Assessment Reports of the IPCC, and especially to the works of the Working Group II on adaptation to climate change. The last WGII report in chronological order is *Climate change 2014: impacts, adaptation and vulnerability* (IPCC, 2014), which is part of the AR5.

Another reference text is *Climate impacts on energy systems: key issues for energy sector adaptation* (Ebinger and World Bank, 2011). This compendium handles more specifically the energy system topic. For example, the authors mention two case studies on energy adaptation, an Albanian one and a Mexican one.

Then, other institutions and researchers have investigated on adaptation of specific energy systems. For example, we can find studies about the Asian and Pacific electric power sector, or the Mediterranean region; investigations on adaptation in Nordic and Baltic countries, the Canaries Islands or in Europe in general; reports which refer to adaptation of energy production and use in the United States; papers about the problems of the nuclear sector and projects related to African developing countries.

Researches on this topic are increasingly growing, but most of them do not treat comprehensively the adaptation issue. The objective of this thesis is to partially cover this gap. The aims that follow are essentially two. The first one is to draw up a comprehensive summary of the adaptation topic, analyzing the three important aspects quoted in the title of the thesis: climate change, energy systems and adaptation. The second purpose is to apply the method of the analysis on specific systems, to set a guideline for the adaptation of whatever electricity system.

The thesis therefore starts with an overview of the state of the art of the adaptation subject. It continues with a brief discussion about the studies of the IPCC, illustrating their works on the current state of scientific knowledge relevant to climate change. Then, the research is carried out for a generic electricity system in order to consider all the aspects which may be affected by climate change. It is examined what is known about the impacts of climate change on natural system and energy system, clarifying the changes on energy resources, energy demand and energy supply. Following, the vulnerabilities of the electricity system due to climate change are recognized. Next, the purpose is to identify those solutions which could be taken to best adapt the energy systems. Ultimately, a case study is analyzed to put into practice the noticed solutions of the generic system. This segment of the thesis is focused on two specific electricity systems, the Spanish and the Italian ones.

STATE OF THE ART

From the end of the 20th century, after the establishment of the IPCC in 1988, the stipulation of the United Nations Framework Convention on Climate Change (UNFCCC) in 1992 and the ratification of the Kyoto Protocol at the COP-3 (Third Conference of the Parties) in 1997, the scientific community has been made vivacious on the environmental problem and climate change. The issue of adaptation was evaluated as an important way to manage climate change. However, at the beginning researchers did not focus much on it. They concentrated more on greenhouse gases reduction, better known as mitigation. Gradually, thanks to the understanding that we can not avoid climate change, the community has partially moved on the adaptation direction. For this reason, now we can rely on lots of records about the adaptation issue.

The Working Group II is the research group of the IPCC that assesses the vulnerability of socio-economic and natural systems to climate change, negative and positive consequences of climate change and options for adapting to it. It assesses in a general way the issue of adaptation. It does not concentrate only on energy systems and adaption of them to climate change. It covers all the sectors which could be affected by climate change, as water resources, ecosystems, food and forests, coastal systems, industry and human health. In a specific section of the Fifth Assessment Report (AR5) (IPCC, 2014) it gives an account of the existing and possible different solutions to adapt sectors from climate change.

IPCC is only one party that does research on adaptation issue, and that considers globally this problem, not focusing on a particular topic. All this kind of researches on adaptation in literature differs on some details, but they all have in common a particular pattern. Their documents can be divided into two distinct sections: the first one concerns the impacts of climate change on the systems that they consider, while the second one treats the adaptation of the systems to climate change. This is a constant of the scientific researches on adaptation. To define possible solutions to climate changes it is crucial to before identify all the impacts that climate change leads to the systems. Later, these general studies examine various topics and systems. They obviously also address adaptation: some give general recommendations on it, others find more specific solutions to specific sectors or regions. For example the study *Global climate change impacts in the United States: a state of knowledge report* (U.S. Global Change Research Program, 2009) summarizes the science of climate change and the impacts of climate change on the United States, now and in the future, but it also deals with some of the actions that society is taking or can take to respond to climate challenge, as adaptation. *Adapting to climate change: the public policy response: public infrastructure* (Neumann and Price, 2009) assesses the threats and needs that multidimensional climate change imposes for public infrastructure. It presents also options for enhancing adaptive capacity through public sector investments. It includes an analysis of energy generation and transmission infrastructure, but the recommendations and conclusions of the paper concern a general adaptation for public infrastructure more than a specific one for energy system. Another example is the *PESETA Research Project* (Ciscar et al., 2009). The main purpose of this publication was to summarize the project methodology and present the main results that can be relevant for the debate on adaptation policies within Europe. The focus was concentrated more on agriculture, river floods, coastal systems, tourism and human health than on energy. Nevertheless, this project reflected the commitment of the European Union on the adaptation problem. The report descended from the study of the European Commission *White Paper* (Commission of the European Community, 2009a) which noted the need to better know the possible consequences of climate change in Europe. The accompanying document *Impact assessment* (Commission of the European Community, 2009b) covered the adaptation problem, raising the profile of adaptation and building a coherent approach at institutional level across the EU.

Some other scientists focused more specifically on energy sectors. Energy systems are one of the major agents which has provoked climate change, therefore the scientific production is prolific about this matter. Even in this case the Working Group II of the IPCC covered the question in its assessment. Some authors studied more this matter, in a very detailed way. The U.S Climate Change Science Program and the Subcommittee on Global Change Research in their synthesis and assessment product *Effects of climate change on energy production and use in the United States* (Wilbanks et al., 2008) summarized what was known about effects of climate change on energy production and use in the United States, and the need to expand the knowledge base about effects of climate change. The main topic was the study of the climate impacts on energy systems, because they considered the most likely adaptation measure in the near term an increase in perceptions of uncertainty and risk of climate change. Other organizations like the World Bank, the Asian Development Bank and the HELIO International, carried out more topical research on the adaptation argument. These studies have in common a particular intention: as many other studies about adaptation to climate change, they firstly give an account of climate impacts. They differ from other studies because they also outline a set of recommendations about adapting energy systems, as for the governments as for users. *Climate impacts on energy systems: key issues for energy sector adaptation* (Ebinger and World Bank, 2011) is an up-to-date compendium of what was known about weather variability, projected climate trends and their impacts on energy service provision and demand. It discusses the emerging adaptation practices and tools which have been observed over the world for managing climate impacts. It also takes into consideration the integration of climate considerations into planning processes and operational practices. It ends with a summary of the essential actions to support adaptation, underlining that without a climate information network we can not support the decision making. The Asian development Bank study *Climate risk and adaptation in the electric power sector* (Asian Development Bank, 2012) aims to highlight and raise awareness on the exposure and vulnerability of the energy sector to climate change in Asia and the Pacific. It also identifies engineering and non-engineering adaptation measures available to each source of energy generation as well as for the distribution and end use of electrical energy. It highlights also the importance to significantly improve coordination and planning among key energy agencies, other governments ministries, energy producers, regulators, governments, and users to cope with climate-induced stresses, which are expected to become significant. *Climate-proofing energy systems* of the HELIO International (Williamson et al., 2009) centers the attention on climate-induced impacts on key energy systems and outlines possible adaptation measures. It provides a series of recommendations to help reinforce the resilience of energy systems.

Some other researches instead deepened the adaptation issue of particular energy systems or particular region, elaborating specific adaptation solution. These studies conducted an in-depth analysis upon energy systems, accounting (as all the studies about adaptation) the impacts of climate on energy systems and revealing emerging adaptation practices and concrete measures for adapting systems and actions to support adaptation. The results greatly differ from case to case, because they depend on specific circumstances and conditions. In the paper *Regional energy demand and adaptations to climate change: methodology and application to the state of Maryland, USA* (Ruth and Lin, 2006) the authors explored potential impacts of climate change on natural gas, electricity and heating oil used by residential and commercial sectors in the state of Maryland in USA. They concluded that there was not the immediate need on large-scale investment in electricity generation and energy delivery systems to meet the energy demands induced by climate change, with the exception of commercial electricity demand. This consideration is due to the fact that energy demand in the region will increase considerably in the future for reasons not directly related to climate change. The authors only suggest to adjust the energy use profiles in that region. The paper *Climate change, nuclear power, and the adaption-mitigation* dilemma (Kopytko and Perkins, 2011) discusses the problem of adaptation and mitigation that descends from the use of nuclear power plants. The authors took in considerations several inland and coastal nuclear power plants (15 reactors at 9 coastal sites in USA and 44 reactors at 15 inland sites in France) to develop five criteria to assess the adaptation-mitigation dilemma. A section of the document examines the impacts of extreme events on inland reactors in France and coastal reactors in United States. In this section we can deduce some adaptation measures that have been taken during these years to adapt various plants to extreme events. All these measures and their results must be considered to develop coherent and useful adaptation strategies to use nuclear plants as mitigation tool. In the conference *Energy & water* of the Canary Island Institute of Technology - ITC (Piernavieja Izquierdo, 2015) the lecturer reported the 2 years ITC project *CLIMATIQUE* (Observatorio cambio climático Canarias - Souss-Massa-Drâa, 2015) whose objectives is the finding of impacts of climate variables in the energy system and the elaboration of particular strategies to cover the adaptation issue on thermal power plants, renewable energy technologies and electricity grid in the Canary Island and in the African region of Souss-Massa-Drâa. At last in the World Bank Study *Climate impacts on energy systems: key issue for energy sector adaptation* (Ebinger and World Bank, 2011) the authors reported two specific studies on Albania's energy system and Mexico's electricity utilities, in addition to the general analysis of energy systems and actions to support adaptation. The World Bank, together with the government of Albania, conducted a series of workshops in Tirana in 2009 on climate risks and vulnerability in the country's energy sector as well as opportunities presented by climate change. They concluded that there are several critical actions that Albania could take to support optimal use of energy, water resources, and operation of hydropower plants. The annex about Mexico discusses Mexico's Electricity Utility Plan for the Attention to Natural Disasters. The objective of the plan is to define the activities and control mechanisms that should be followed to affectively deploy the material and human resources necessary to restore electricity service after natural disasters.

Finally, some particular papers treat the adaptation problem under a particular point of view. These documents normally follow the basic design impacts-adaptation. Nonetheless, in addition they discuss on specific points associated to climate change and adaptation matter. IDDRI, CIRED-Meteo France and CIRCE produced the report *The future of Mediterranean. From impacts of climate change to adaptation issue*s (IDDRI, 2009), in which they provide a general framework for the implementation of adaptation in the Mediterranean context, based on a number of important clarifications and accompanied by operational recommendations. The particular treated question was the linkage between adaptation and mitigation. Too often these two strategies were considered as alternative options in the fight against the effects of climate change. But, even if we stop GHG emissions immediately (if we only mitigate), those that have already been issued will still lead to climate changes. So, the path of adaptation is therefore inevitable. Adaptation and mitigation are dealt with by different communities: this distinction should not obscure a number of interrelations between mitigation and adaptation. There are adaptation actions that have consequences on mitigation, and vice versa mitigation actions that have consequence on adaptation. The EEA Technical Report *Vulnerability and adaptation to climate change in Europe* (European Environment Agency, 2005) was prepared with the objectives to provide information on vulnerability in Europe, to facilitate information sharing among EEA member countries, to contribute on adaptation strategies discussion and to identify current and future information needs. The singular thing here is the particular definition of vulnerability reported by authors. Vulnerability is the residual impacts of climate change after adaptation measures have been implemented. This means that vulnerability is considered as a result of adaptation measures, which is useful to identify challenges for climate change adaptation strategies. Next, HELIO International in its *Climate-proofing energy systems* (Williamson et al., 2009) explained its approach in order to help identify policies and measures that can best facilitate and support adaptation activities: to develop a set of indicators to assess the vulnerability and resilience of national-level energy systems to climate change. They chose 10 sub-Saharan countries as first “testing ground” of its indicators, because Africa is a very vulnerable continent to climate change and climate variability, as IPCC Working Group II also said. Compared to mitigation, where a common metric in terms of “ton of CO_2 equivalent reduced” has been used for many years, evaluation of adaptation measures is still in its infancy. There are no commonly accepted parameters and indicators to compare adaptation needs and the effectiveness of adaptation measures. So HELIO International developed a methodology and a series of indicators in line with the guiding principle that the underlying metric must be generally available for most countries. If calculation is required to derive an indicator it must be simple.

Considering the current available studies about adaptation to climate change, we can state that there is no research on adaptation of energy systems under a comprehensive point of view. Most of the studies discuss the impacts of climate change on natural and human systems, and do not focus specifically on energy system. The aim of this thesis is to cover the adaptation of energy systems, starting from the evaluation of future climate change, continuing with the assessment of impacts of climate change on energy systems and the vulnerabilities of these, and concluding with a set of adaptation measures to construct a resilient energy structure.

PART A

CLIMATE CHANGE AND IMPACTS ON ENERGY SYSTEMS

CHAPTER 1

THE CLIMATE CHANGE SCENARIOS

> Human influence on the climate system is clear. This is evident from the increasing greenhouse gas concentrations in the atmosphere, positive radiative forcing, observed warming, and understanding of the climate system. (IPCC, 2013, p.15)

According to the literature, an essential, necessary and critical step of the adaptation analysis is the investigation of the effects of climate change on energy systems. The understanding of future climate change and the study of elaborated scenarios have a fundamental importance, to find the various impacts that we can notice on different systems comprehensively. To this extent the first step of the adaptation research is to understand what are the most used climate change scenarios to detect the several effects that climate change may produce on energy systems.

The IPCC is the reference for research on climate change: it is the leading international body for the assessment of climate change. The essential purpose of the thousands of scientists from all over the world that contribute to the work of the IPCC on a voluntary basis is to review and to ensure an objective and complete assessment of the current literature on climate change and related issues, as adaptation and mitigation. Almost all researchers from all over the world that investigate on adaptation base their studies on the work and investigations that IPCC does about climate scenarios, which reflect on the elaboration of the IPCC Representative Concentration Pathways (RCPs). The RCPs are a set of four new scenarios developed for the climate modeling community as basis for long-term and near-term modeling experiments.

Before starting to examine the impacts of climate changes it’s necessary a clarification of the latest work of the IPCC – the Fifth Assessment Report (AR5) – focusing on the RCP scenarios and their structure.

1.1 The IPCC Fifth Assessment Report and the Representative Concentration Pathways

The IPCC Working Group I (WGI) assesses the physical scientific aspects of the climate system and climate change in the first part of the IPCC Fifth Assessment Report *Climate change 2013: the physical science basis* (IPCC, 2013). In this study the various members of the WGI introduce a new set of climate change scenarios – the RCPs – which are useful instruments to elaborate new projections of climate change and impacts of climate change to natural, human and energy systems. The RCPs are an important development in climate research and provide a potential foundation for further research and assessment, including emissions mitigation and impact analysis. The RCPs are the product of an innovative collaboration between integrated assessment, climate and terrestrial ecosystem modelers and emission inventory experts. The resulting product forms a comprehensive data set with high spatial and sectorial resolutions for the period extending to 2100.

The methodology used to elaborate this set of scenarios of climate and impacts projections is completely new. The approach used in the AR5 is totally different from the one utilized in the previous assessments. Figure 1.1 (Moss et al., 2007, p.11) shows the differences between the old and new one. The new parallel approach should provide better integration, consistency and consideration of feedbacks and more time to assess impacts and responses. The research community needs new scenarios, as pointed out by Moss et al. (Moss et al., 2010). First, more detailed information was needed for running the current generation of climate models than that provided by any previous scenarios sets. Second, there was an increasing interest in scenarios that explicitly explore the impact of different climate policies in addition to the no-climate-policy scenarios explored so far (the SRES: Special Report on Emissions Scenarios). Finally, there was an increasing interest in exploring the role of adaptation in more detail. The Panel also recognized that the development of scenarios for AR5 would not be undertaken as part of the IPCC process, leaving new scenario development to the research community. The community subsequently designed a process of three phases, which involves the so called "parallel approach":

1. Development of a scenario set containing emission, concentration and land-use trajectories – referred to "*Representative Concentration Pathways*" (RCPs).
2. A parallel development phase with climate model runs and development of new socio-economic scenarios.
3. A final integration and dissemination phase.

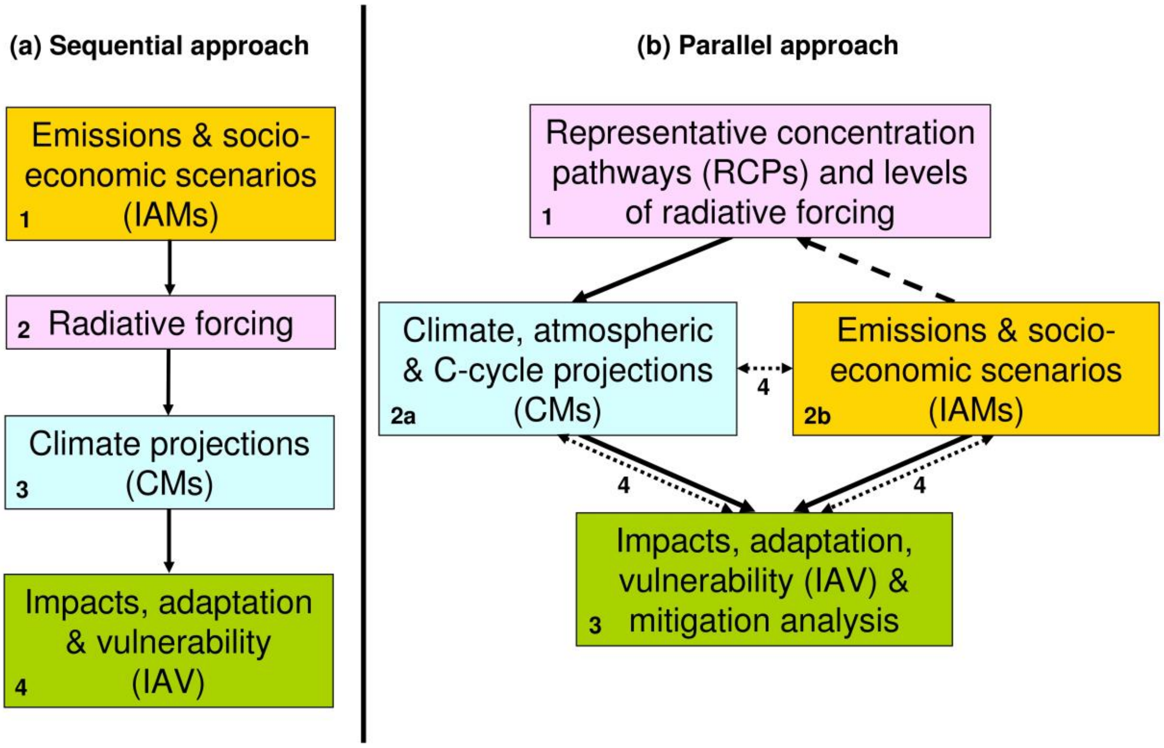

Figure 1.1 Approaches to the development of global scenarios: (a) previous sequential approach; (b) parallel approach. Numbers indicate analytical steps (2a and 2b proceed concurrently). Arrows indicate transfers of information (solid), selection of RCPs (dashed), and integration of information and feedbacks (dotted) (Moss et al., 2007, p.iv)

The main purpose of the first phase (the development of the RCPs) is to provide information on possible development trajectories for the main forcing agents of climate change, consistent with current scenario literature allowing subsequent analysis by both Climate Models (CMs) and Integrated Assessment Models (IAMs)[1]. The crucial point of the new approach is the quantification of Radiative Forcing (RF) that forms the Representative Concentration Pathways. The procedure is completely different from the previous sequential approach, where the emissions and socio-economic scenarios supplied the evaluation of the radiative forcing. The RCPs are not associated with unique socioeconomic assumptions or emissions scenarios but can result from different combinations of economic, technological, demographic, policy, and institutional futures ("Socio-Economic Data and Scenarios," 2014). RF is defined in AR5, as in previous IPCC assessments, as the change in net downward flux (shortwave + longwave) at the tropopause after allowing for stratospheric temperatures to readjust to radiative equilibrium, while holding other state variables such as tropospheric temperatures, water vapor and cloud cover fixed at the unperturbed values (IPCC, 2013, p.53). In a simpler way, radiative forcing is a measure of the net change in the energy balance of the Earth system in response to some external perturbation, with positive RF leading to a

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[1] The term "Climate models" is used for all kinds of models used for studying the global climate system, such as Earth-System Models of Intermediate Complexity (EMICs), Atmosphere-Ocean coupled Global Circulation Models (AOGMCMs) and Earth System Models (ESMs). The term Integrated Assessment Model refers to models that combine natural science and socio-economic aspects of climate change primarily for the purpose of assessing policy options for climate change control.

warming and negative RF to a cooling. The external perturbations are especially human activities that have changed and continue to change the Earth's surface and atmospheric composition. Some of these changes have a direct or indirect impact on the energy balance of the Earth and are drivers of climate change. These drivers are: direct change in the atmospheric composition via emissions of gases or particles (CO_2, CH_4, N_2O, CFCs and halocarbons); indirect change in the atmospheric composition via atmospheric chemistry; anthropogenic aerosols-radiation interaction (ari) and aerosol-cloud interaction (aci); land use changes such as deforestation; natural drivers of climate change like solar and volcanic forcings. All these drivers turn into a positive total radiative forcing, which has led to an uptake of energy by the climate system. The largest contribution to total radiative forcing is caused by the increase of CO_2 atmospheric concentration since 1750 (IPCC, 2013, p.13).
Scenarios used in Working Group I have focused on anthropogenic emissions and do not include changes in natural drivers such as solar or volcanic forcing or natural emissions. For the IPCC AR5 the scientific community identified a specific emission scenario (including data on land use and land cover) from the peer reviewed literature to represent the span of the radiative forcing literature at the time of their selection and thus facilitate the mapping of a broad climate space. These were given the label 'Representative Concentration Pathways'. The term "Representative" signifies that each RCP provides only one of many possible scenarios that would lead to the specific radiative forcing characteristics. "Pathway" emphasizes that not only the long-term concentration levels are of interest, but also the trajectory taken over time to reach that outcome. They were identified by their approximate total radiative forcing target in year 2100 relative to 1750: 2.6 W/m^2 for RCP2.6, 4.5 W/m^2 for RCP4.5, 6.0 W/m^2 for RCP6.0 and 8.5 W/m^2 for RCP8.5. In 2011 the total anthropogenic RF relative to 1750 was 2.29 [1.13 to 3.3] W/m^2, and it has increased more rapidly since 1970 than during prior decades (IPCC, 2013, p.13).

Climate and impact research communities have cooperated to design the alternative parallel approach for creating and using scenarios. In the parallel phase of the process, climate and integrated assessment modelers will work simultaneously rather than sequentially (see Figure 1.2). The climate modelers will conduct new climate model experiments and produce new climate scenarios using the time series of emissions and concentrations from the four RCPs. The Coupled Model Intercomparison Project Phase 5 (CMIP5) is the new multi-model experiment (coordinated through the World Climate Research Programme) that presents an unprecedented level of information on which to base assessments of climate variability and change. CMIP5 is much more comprehensive than the preceding CMIP3 multi-model experiment. CMIP5 has more than twice as many models and many more experiments. A larger number of forcing agents are treated more completely in the CMIP5 models, particularly on aerosols and land use. Then, in parallel with the development of climate scenarios based on the RCPs, new socio-economic scenarios will be developed to explore important socio-economic uncertainties affecting both adaptation and mitigation. The new socio-economic scenarios will be integrated with the new climate scenarios.

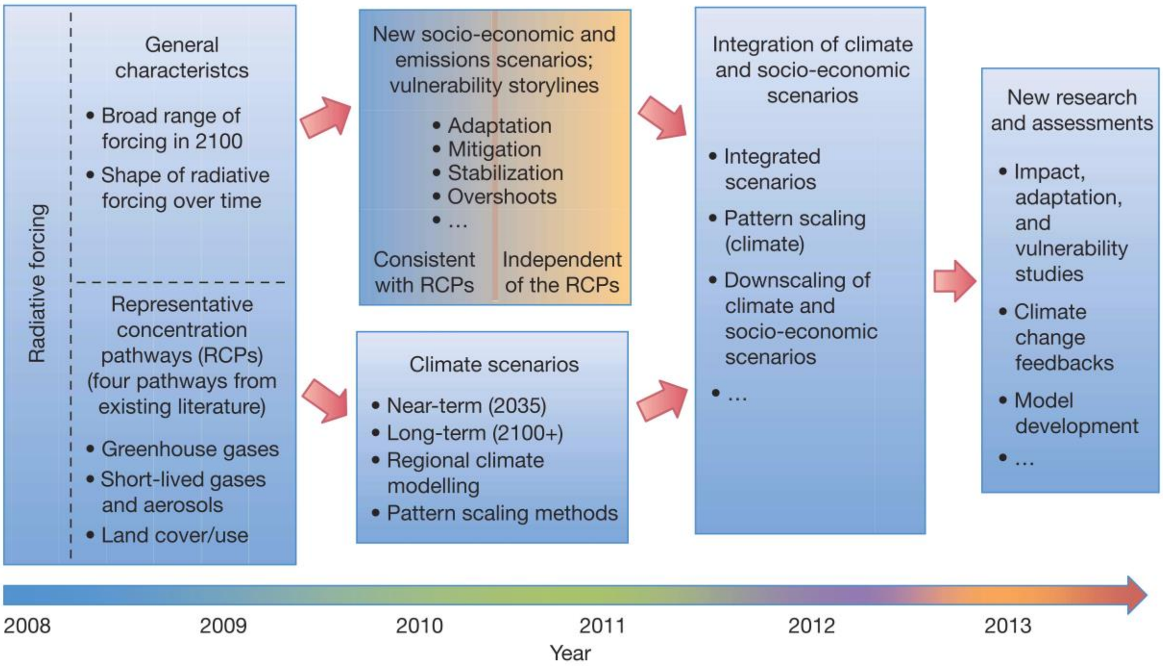

Figure 1.2 The process of developing new scenarios that will be used in future climate change research and impact assessment (Moss et al., 2010, p.752)

The result of this process is the achievement of projections of changes in the climate system. These projections are made using a hierarchy of climate models ranging from simple climate models, to intermediate complexity, to comprehensive climate and Earth System Models, which belongs to the framework of the Coupled Model Intercomparison Project Phase 5 (CMIP5) of the World Climate Research Programme. The new set of scenarios, the RCPs, are used for the new climate models simulations carried out by the framework of the CMIP5. The resulting projections are normally for the end of the 21st century (2081-2100). To place such projections in historical context, it is necessary to consider observed changes between different periods. The various projections have in common some peculiarities. Projections for the next few decades show spatial patterns of climate change similar to those projected for the later 21st century but with smaller magnitude. Natural internal variability will continue to be a major influence on climate, particularly in the near-term and the regional scale. And then, projected climate change based on RCPs is similar to AR4 in both patterns and magnitude, after accounting for scenario differences. The overall spread of projections for the high RCPs is narrower than for comparable scenarios used in AR4.

As we have seen, the approach used in the AR5 by the scientific community to develop climate change projections and emissions and socio-economic scenarios is totally different from the previous sequential approach. This dissimilarity causes differences between the results of the analysis. Climate change predictions and impacts projections derived from the parallel approach and RCPs scenarios, are different from the ones obtained from the sequential approach and the SRES scenarios. But most of the available studies and researches on adaptation have still used the data that come from the AR4 and the sequential approach. For example, whereas WGI AR5 is based primarily on results from the RCP CMIP5, the WGII AR5 also uses results from the SRES CMIP3, and thus identifies similar or parallel scenarios from each set. (IPCC, 2014, p.178). For this reason, it is essential to outline SRES scenarios and the sequential approach, to understand the data we can get from the literature about adaptation, climate change and impacts of climate change to natural, human and energy systems.

1.2 The Special Report on Emissions Scenarios and differences with RCPs

The Special Report on Emissions Scenarios (SRES), published by the IPCC in 2000, describes the emissions scenarios that have been used to make projections of possible future climate change, for the IPCC Third Assessment Report (TAR), published in 2001, and in the IPCC Fourth Assessment Report (AR4), published in 2007 ("Emission Scenarios | WMO," n.d.).
In *Emissions scenarios. A special report of IPCC Working Group III* (Intergovernmental Panel on Climate Change and Working Group III, 2000) there are shown the main characteristics of the scenarios used in Third and Fourth Assessment Report. This set of scenarios was developed to represent the range of driving forces and emissions in the scenario literature, to reflect current understanding and knowledge about underlying uncertainties.

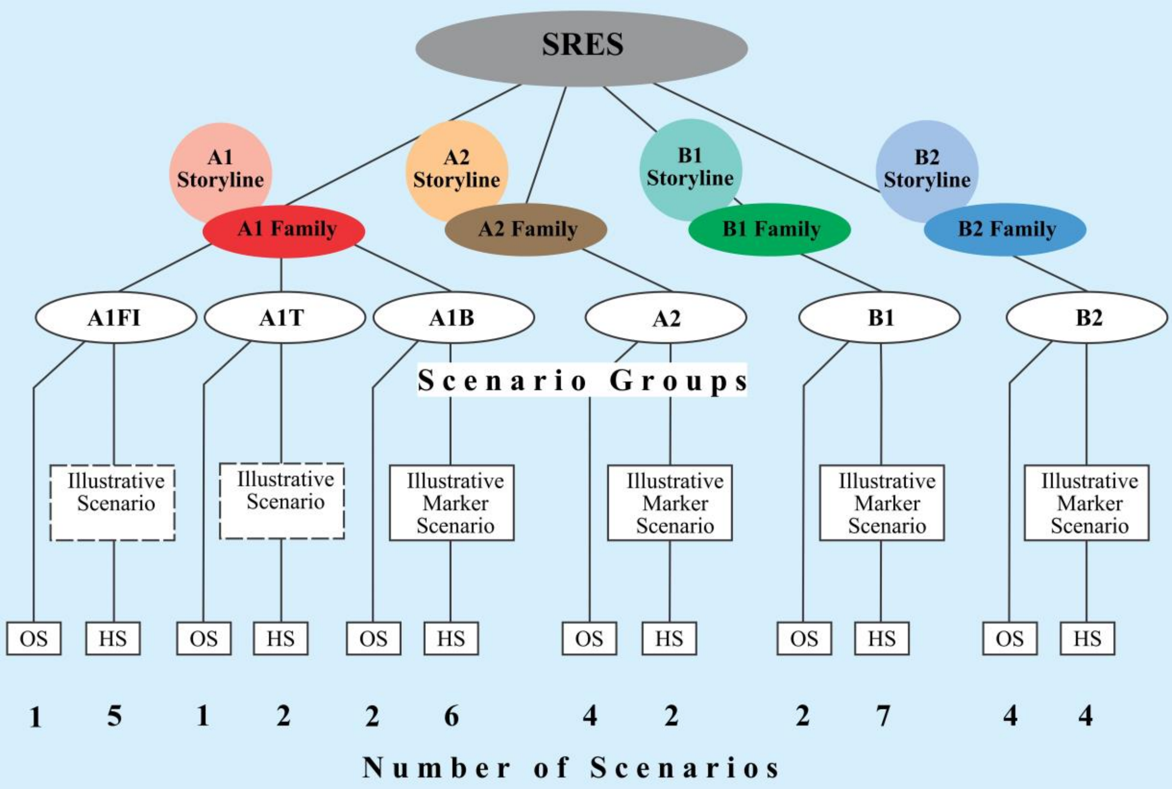

Figure 1.3 Schematic illustration of SRES scenarios (Intergovernmental Panel on Climate Change and Working Group III, 2000, p.4)

The scenarios are based on an extensive assessment of driving forces and emissions in the scenario literature, alternative modeling approaches, and an "open process" that solicited wide participation and feedback. Four different narrative (illustrated in Figure 1.3) storylines were developed to describe consistently the relationships between emission driving forces and their evolution and add context for the scenario quantification.

Each storyline represents different demographic, social, economic, technological, and environmental developments, which may be viewed positively by some people and negatively by others. The scenarios cover a wide range of the main demographic, economic and technological driving forces of GHG and sulfur emissions and are representative of the literature. Each scenario represents a specific quantitative interpretation of one of four storylines. All the scenarios based on the same storyline constitute a scenario "family". The scenarios do not include additional climate initiatives, which means there are no scenarios which include explicitly implementation of the United Nations Framework Convention on Climate Change (UNFCCC) or emissions targets of the Kyoto Protocol. For each storyline several different scenarios were developed using different modeling approaches to examine the range of outcomes arising from a range of models that use similar assumptions about driving forces.

The differences between the SRES and the RCPs are many and huge. Firstly, the development of global scenarios is completely different, as we have already seen. The sequential approach ensured that SRES were run in sequence, which implied a loss of time because, in order to incorporate new or changed data, you had to go back and re-run all the simulation. The new RCPs employ a process intended to make the modelling less time-consuming, more flexible, with a reduced economic cost of computation.

The most innovative aspect of the RCPs is that instead of starting with socio-economic 'storylines' from which emission trajectories and climate impacts are projected (the SRES methodology), each RCPs describe an emission trajectory and concentration by the year 2100, and consequent forcing. Each trajectory represents a specific synthesis drawn from the published literature. From this baseline, researchers can then test various permutations of social, technical and economic circumstances.

For the first time, policy decisions can be tested. Previous scenarios were described as 'no-policy', meaning the scenarios did not respond to changes driven by political or legislative inputs, so mitigation or adaptation strategies could not be incorporated. SRES specified the socio-economic circumstances for each scenario, which essentially locked in the options for socio-economic change (and led to a proliferation of SRES scenarios – 40 in total). Models were programmed to generate emissions and subsequent climate scenarios. The socio-economic variables of the SRES scenarios were socially and policy-prescriptive, the emissions were inflexible and climate change outcomes were not. By fixing the emissions trajectory and the warming, RCPs come at the problem the other way round. Socio-economic options become flexible and can be altered at will, allowing considerably more realism by incorporating political and economic flexibility at regional scales. Policy decisions on mitigation and adaptation can be tested for economic efficacy, both short and long term. Researchers can test various socio-economic measures against the fixed rates of warming built into the RCPs, to see which combinations of mitigation or adaptation produce the timeliest return on investment and the most cost-effective response.

Summarizing, this new approach descends from the pathway of radiative forcing and emissions that was chosen as new starting point of the analysis. Many different socio-economic futures are possible leading to the same level of radiative forcing. On the other hand, starting with assumptions related to population growth, economic development or technology delays the availability of the resulting climate scenarios for impact research and assessment, because scenarios were developed and applied sequentially in a strict linear causal chain.

CHAPTER 2

CLIMATE CHANGE AND IMPACTS ON ENERGY SYSTEMS

> A strong, credible body of scientific evidence shows that climate change is occurring, is caused largely by human activities, and poses significant risks for a broad range of human and natural systems. (The National Academy of Sciences, 2010)

As a result of the growing recognition that climate change is underway and poses serious risks for both human societies and natural systems, decision makers are asking what is happening and what can we do to respond to it. Nations need a comprehensive, integrated and flexible climate change research that should be closely linked with action-oriented programs at all levels. The areas of interest for decision makers extend from changes in climate system to changes in natural resources as freshwater; from agriculture and fisheries to public health, cities, national and human security; from transportation system to energy system and its impacts. With regard to these topics, this section will center the attention on climate change and its impacts on energy systems.

2.1 The paths of climate impacts

The diagram of Figure 2.1 shows the various relationships that exist between climate change and several sections of the energy system.

As we can see the chart is divided into two parts. The upper concerns natural and physical systems that considers the major climatic tendencies which constitute climate change, temperature, precipitation and extreme events. The lower part regards the impacts that climate change and its consequences produce on all sectors that constitute an energy system. This is the main section of this part of the thesis, because the aim of the study is the analysis of energy systems and the adaptation of it.

In the lower portion we consider water as part of energy system because it is a fundamental resource for energy demand and supply. Besides, we diversify it from general energy resources because it has a greater importance. Water and energy are linked through numerous interactive pathways affected by a changing climate.

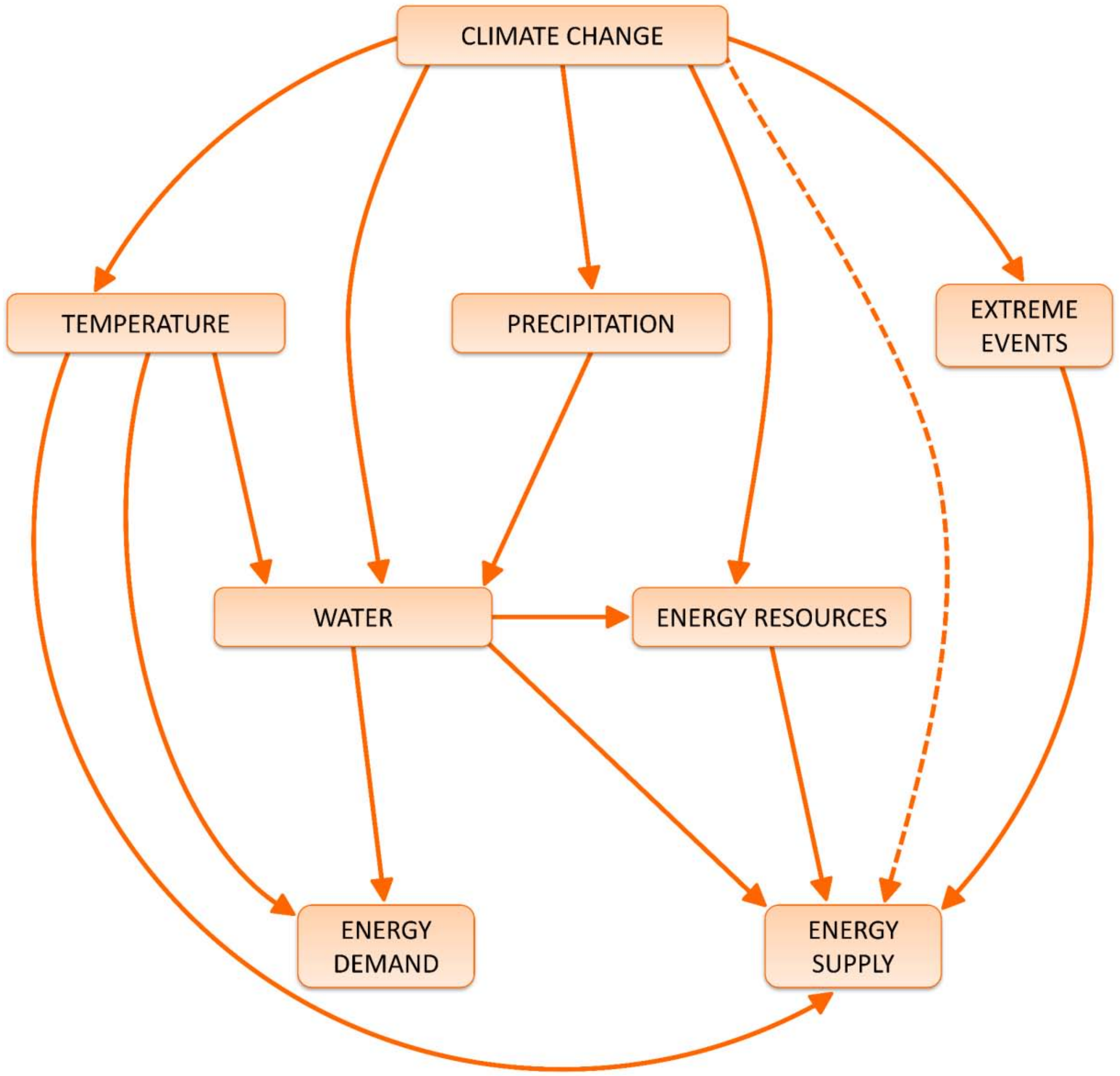

Figure 2.1 Structure of climate change's impacts on energy systems. Created by author

Many energy sources require significant amounts of water and produce a large quantity of wastewater that needs energy for treatment (see Table 2.1). Energy systems should be managed considering water system, and its management, because these two areas have a strong vice-versa relationship. Thus the analysis, the management and the control of these two huge systems can not be divided one from the other, and for this reason we consider it as part of the energy system.

Table 2.1 The water-energy nexus. Based on Figure WE-1 from Climate change 2014: impacts, adaptation, and vulnerability. Part A: global and sectoral aspects *(IPCC, 2014, p. 164)*

WATER FOR ENERGY
Cooling of thermal power plants
Hydropower
Irrigation of bioenergy crops
Extraction and refining
ENERGY FOR WATER
Extraction and transportation
Water treatment/desalination
Wastewater, drainage, treatment and disposal

The view and the classification proposed here are not exhaustive as the complexity of the chains of impact is considerable. The aim is only to give an overview by showing how climate change will take place, and the relative magnitude. The same problem comes out for the upper and the lower part of the diagram: the arrangement of the numerous impacts of climate change on natural system and electric energy system is subjective and debatable. The assessment is as much as possible accurate to the literature, but it obviously exhibits a subjective perspective.

As regards the structure of the paths of impacts, we can observe that the connection between “Climate change” and “Energy supply” is different from the others. The dashed arrow represents an instrumental connection between those two elements, used to put in place the mitigation issue on the impacts’ analysis. Instead, others connections display a direct impact between the elements.

2.2 Climate change, its major consequences and physical impacts

The point of departure of the entire assessment of climate impacts on energy system is the evaluation of physical impacts of climate change on natural systems.

There is high agreement and robust evidence that climate change occurs, and it is affecting natural, physical and human systems. Observations of changes in the climate system, and their magnitude, are significant for the adaptation issue, because the wide changes of physical system are the drivers that affect the energy system. These drivers could be gathered into three major climatic consequences. These are the change of temperatures, of precipitation pattern and the frequency and intensity of extreme events. The various shown data are taken from the Working Group I contribution to the Fifth Assessment Report of the IPCC, unless noted otherwise.

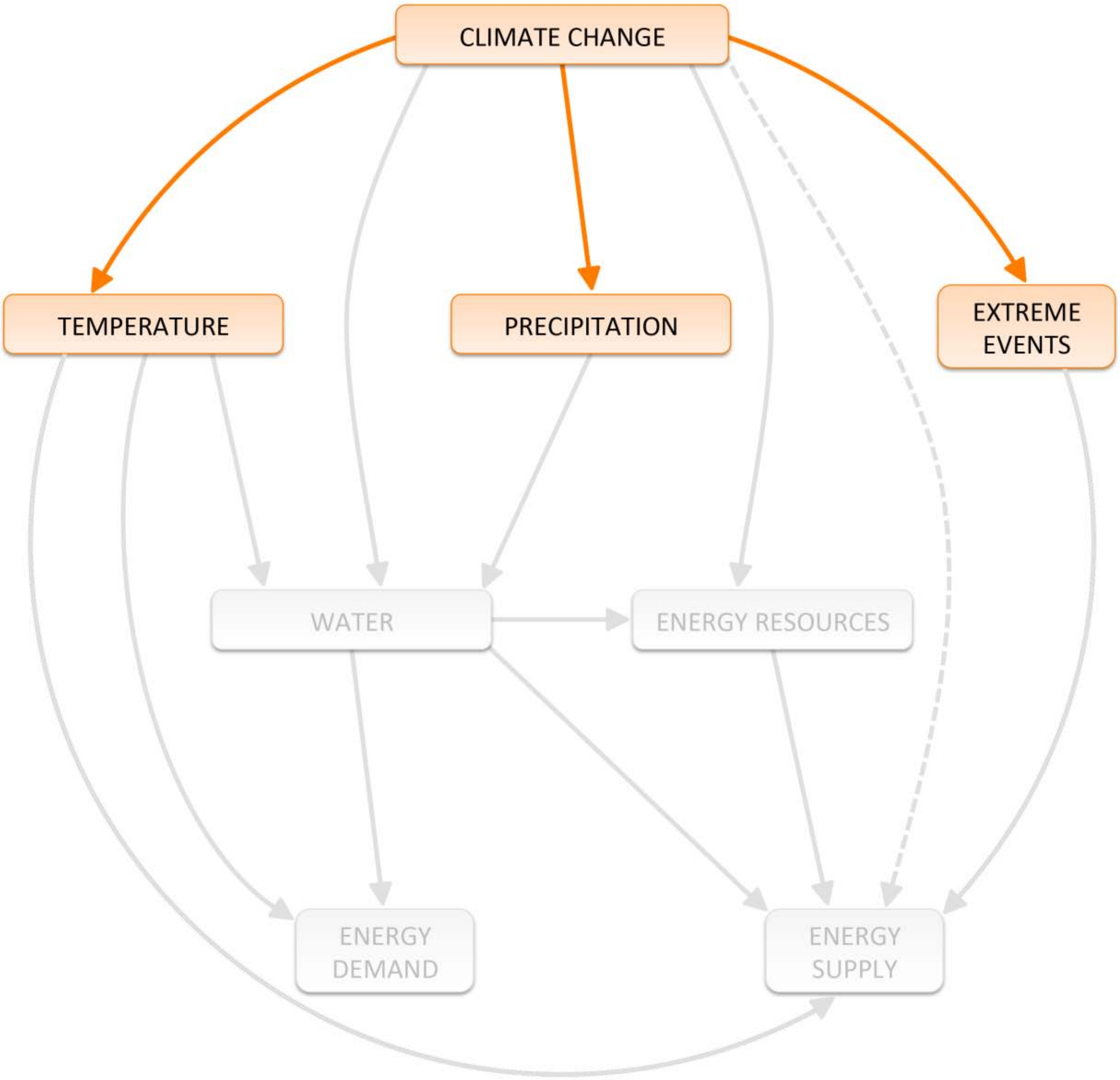

Figure 2.2 Physical impacts of climate change on natural systems. Created by author

Temperature changes

Each of the last three decades has been successively warmer at the Earth's surface than any preceding decade since 1850. (IPCC, 2013, p.5)

Climate change has led, is leading and will lead to an increase of temperature in almost all of the entire globe. We could observe a raise of temperature in several elements that constitute the natural system, as atmosphere, land, ocean, rivers, lakes, and glaciers. To appreciate the intensity of the warming, scientists and researchers weigh some parameters as global mean surface temperature, free atmospheric temperature, troposphere temperature and ocean temperature. Except for some particular cases projections indicate a general warming with high confidence.

The globally averaged combined land and ocean surface temperature raised by 0.85°C over the period 1880 to 2012. Then, ocean warming dominated the increase in energy stored in the climatic system, accounting for more than 90% of the energy accumulated between 1971 and

2010. The ocean warming is largest near the surface: the upper 700m warmed by 0.11°C per decade over the period 1971 to 2010, storing more than 60% of the net energy increase in the climate system. The remaining 30% is stored in the ocean below 700m.

Precipitation changes

Precipitation pattern has changed in the 20th century. Over the mid-latitude land areas of Northern Hemisphere precipitation has increased since 1901, with higher confidence after 1951. But changes in precipitation are hard to measure with the existing records, due to the greater difficulty in sampling precipitation. At present there is medium confidence that there has been a significant human influence on global scale changes in precipitation patterns, including increases in Northern Hemisphere mid-to-high latitudes. It is more likely that the changes have been influenced by natural internal variability. Projected changes in the water cycle over the next few decades show similar large-scale patterns to those towards the end of the century, but with smaller magnitude, and as for precipitation observations it is expected that projected changes will be strongly influenced by natural internal variability and may be affected by anthropogenic emissions. Anyway, projections show an increase of precipitation depending on the latitude: annual mean precipitations will increase in high and mid latitudes and in the equatorial Pacific Ocean, and they will not decrease in subtropics.

Extreme events changes

Changes in many extreme weather and climate events have been observed since 1950. These severe episodes appear in different forms, affecting temperature, precipitation and atmospheric circulation.

Cold days and nights has decreased and warm days and nights has increased on the global scale. The frequency of heat waves has increased in Europe, Asia and Australia, and scientists are almost certain that in the future there will be more frequent hot and fewer cold temperature extremes over most land areas. Heat waves will occur with higher frequency and duration. However, occasional cold winter extremes will continue to take place.

The frequency and intensity of heavy precipitation has varied: in North America and Europe has likely increased, while in other continents there is not so much confidence about it. For the near and long term global projections confirm a clear tendency for increases in heavy precipitation events in the global mean, but there are significant variations across regions. For example, extreme precipitation events will become more intense and more frequent over most of the mid-latitudes land masses and over wet tropical regions.

Cyclone’s and hurricane’s activity has been altered in the 20th century. AR4 concluded that an increasing trend had occurred in intense tropical cyclone activity since 1970 in some regions but that there was no clear trend in the annual numbers of tropical cyclones. Subsequent assessment and more recent literature indicate that it is difficult to draw firm conclusions with respect to the confidence levels associated with observed trends prior to the satellite era.

However, future projections of tropical cyclones activity assert that there will be a decrease or an unchanged activity during the 21st century. And globally the area encompassed by monsoon systems will increase over the century while monsoon winds will weaken and monsoon precipitation will intensify due to the increase in atmospheric moisture.

These climatic trends and impacts on natural and physical systems have influenced and will influence the energy system, and in particular the electric one, mostly following the pathway which is shown in the framework of Figure 2.1.

2.3 Climate change's impacts on energy system

This paragraph discusses what is known about how energy systems can be affected by changing climate conditions: it can be influenced through many ways.

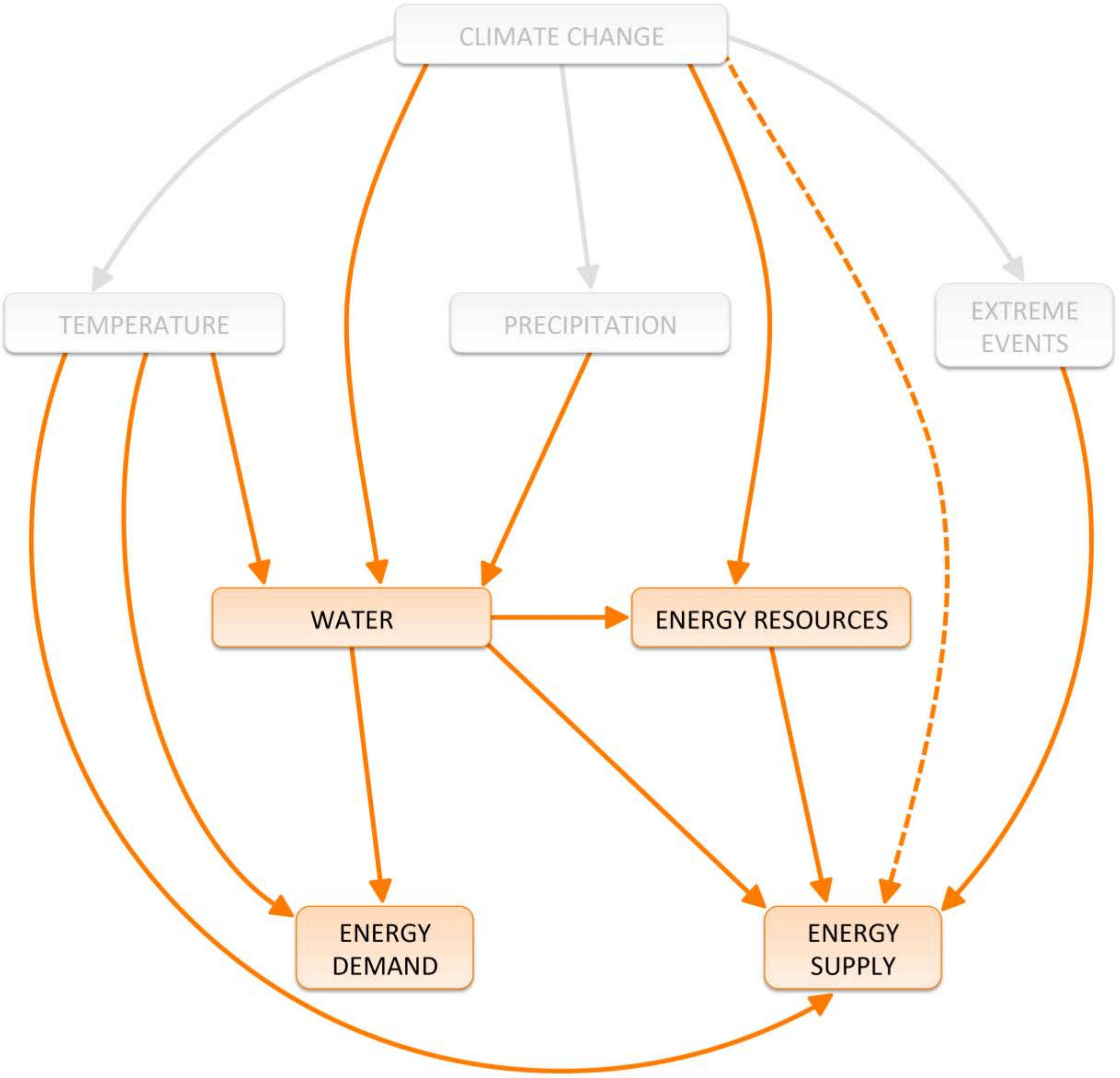

Figure 2.3 General framework about climate change's impacts on energy system. Created by author

Although impacts on energy supply and demand are the most immediate, climate change can also affect various other aspects of the energy sector, such as energy endowment, energy transportation and infrastructure, or have indirect effects through other economic sector.

In this section the energy system is considered subdivided into three main aspects, as it can be observed in Figure 2.3 (which represent the second part of the diagram of Figure 2.1): energy resource, energy demand and energy supply. As above mentioned, in this portion we think about water as part of the energy entity. We consider it as an isolated component of the system, specifically isolated from energy resource, because it has a greater importance than other energy sources; and it is firmly linked and it strongly affects many portions of the structure.

Energy resources concerns the amount of primary energy available. In this field we distinguish fossil fuels endowments, which refer to energy stock and how climate change may affect access to these resources, and renewable energy endowments, which refer to a flux of energy that is closely related to climate parameters. Energy demand relates to final energy use. This can be affected by rising temperatures and changes in rainfall patterns. Households consumption, industry demand and agriculture requests are part of this area. The analysis of how climate variables affect energy demand usually is underrated, but it is an important theme for energy planning and operations. Finally, energy supply focuses on the technologies that convert primary energy into a form that can be used by consumers. Energy transformation facilities can be affected by climate change in different ways. And the major share of the current energy system (and even the energy facilities under construction or planned to be built in the next years) will likely remain operational under new climate conditions given the long life span of energy infrastructure. So an accurate analysis of the current energy system supply is necessary and undeniable.

This section will attempt to cover a wide variety of impacts that climate change may have on energy systems. Its structure covers the following points: it starts from water and continues to other energy resources, energy demand and energy supply. The analysis does not follow the cause-and-effect pattern: instead it’s given a backward account of the distinct elements which affect each system unit.

Most of the data and trends are collected from *Climate change 2013: the physical science basis: Working Group I contribution to the Fifth assessment report of the Intergovernmental Panel on Climate Change* (IPCC, 2013). Otherwise it will be mentioned the considered source.

2.3.1 Impacts on water

In this analysis water is considered as part of energy resources, but also as an independent and important entity which has a strong correlation with all that is part of energy system. Water, as independent body, influences the various units which constitute the energy system, as energy resource, energy demand and energy supply. Therefore, in this section we outline impacts and modification of the water body, considering water as something unrelated to energy system.

In conclusion we describe the impacts of climate change and its consequences on the various parts that constitute the water system, as water bodies, glaciers and oceans. Figure 2.4 shows the points covered in the analysis.

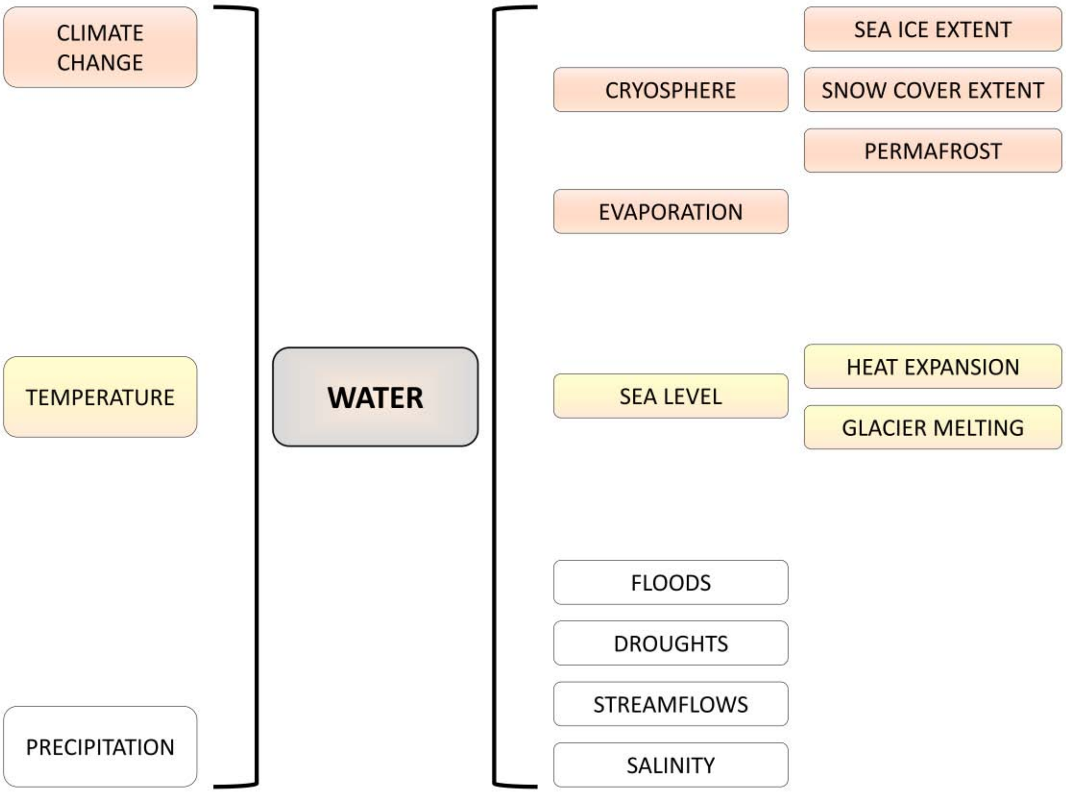

Figure 2.4 Climate change's impacts on water system. Created by author

Climate change

Climate change influences numerous elements which are part of the water system. The cryosphere is one of them. Cryosphere is the collective term for the components of the Earth system that contain a substantial fraction of water in the frozen state. It comprises several components: snow, river and lake ice; sea ice; ice sheets, ice shelves, glaciers and ice caps. All components of the cryosphere are inherently sensitive to changes in air temperature and precipitation, and hence to climate change in general. Arctic and Antarctic sea ice extent decreased over the period 1979-2012, and they will continue to shrink and thin all year round during the 21st century as the annual mean global surface temperature raises. Snow cover extent has decreased in the Northern Hemisphere, especially in spring, and the CMIP5 models simulate a weak decrease during the last two decades of the 21st century. Permafrost temperatures have increased in most regions since the early 1980s although the rate of increase has varied regionally: significant permafrost degradation has occurred in the Russian

European North. Recent projections of the extent of near-surface permafrost indicate substantial degradation of it, and thaw depth increasing over much of the permafrost area. The projected changes in permafrost are a response to warming but also to changes in snow conditions, because snow properties and their seasonal evolution exert significant control on soil thermal state.

Evaporation is another element of the water system that is affected by climate change. To be more accurate, evaporation is a part of the hydrological cycle, and for this reason it is highly influenced by the precipitation pattern. On a global scale, evapotranspiration over land increased from the early 1980s up to the late 1990s: after 1998 a lack of moisture availability in Southern Hemisphere land areas has acted as a constraint to further increase of global evapotranspiration. Future evaporation rate will be different from region to region: over land it will have the same pattern as increases and decreases in precipitation.

Temperature

We can state that an element that belongs to the water system is almost influenced only by temperature changes and not by climate change in general. This element is the sea.

It was found that the contributors to global mean sea level rise are the thermal expansion, the changes in aggregate glacier volume (land-ice masses), the Greenland and Antarctic ice sheet's mass balance and the water storage on land. Past observations of oceans revealed that the warming of the upper 700 m of sea from 1971 to 2010 caused an estimated mean rate of rise of 0.6 mm/yr. Observations of the contribution to sea level rise from warming below 700 m are still uncertain due to limited historical data, especially in the Southern Ocean. But some studies have found a significant warming trend between 1000 and 4000 m: the estimated total contribution of warming below 2000 m to global mean sea level rise between about 1992 and 2005 is 0.1 mm/yr.

Researchers then have investigated in depth future changes of oceans and sea level rise, noticing that the major contributors for future sea level rise are the heat expansion and the melting of glaciers. The term "glaciers" excludes contributions of Antarctica's glaciers but includes contributions of the peripheral glaciers of the Greenland ice sheet.

Precipitation

The change of precipitation pattern causes different repercussions on water system and other fields. Principally two effects stand out: floods and droughts. Flooding occurs most commonly from heavy rainfall when natural watercourses do not have the capacity to convey excess water. Drought conditions occur for many reasons. We most often think about drought in relation to precipitation, assessing the degree of dryness and the duration of the dry period. This is known as a meteorological drought. But we can also think about hydrological drought, or how decreases in precipitation affect streamflow, soil moisture, reservoir and lake levels,

and groundwater recharge ("Causes of Drought," n.d.). To sum up, the variability of precipitation pattern could result in floods and droughts presence.
These events are influenced by climate change: however, there continues to be a lack of evidence regarding the sign of trend in the magnitude and frequency of floods and droughts on a global scale due to climate change.

The most evident flood trends appear to be in northern high latitudes, where observed warming trends have been largest. Some studies for Europe show evidence for upward, downward or no trend in the magnitude and frequency of floods: thus, there is currently no clear and widespread evidence for observed changes in flooding except for the earlier spring flow in snow-dominated regions. The earlier spring flow is caused by changes in precipitation pattern and changes in temperatures. The California Climate Change Center elaborated a report in which is described the earlier spring flow problem. In this report, *Climate change impacts on high*-elevation hydropower generation in California's Sierra Nevada: a case study in the upper American river (California Climate Change Center, 2006). They explain that under a climate change scenario, California's hydrology would experience an earlier timing of streamflows. This shift is associated with the increase in temperature, leading to a higher proportion of precipitation falling as rain (as compared to snow) and an earlier spring snowmelt runoff. This report confirms that climate change modifies precipitation patterns and then the seasonal inflows, which could affect, for example, the hydropower generation in a basin.

Assessments of changes in drought characteristics with climate change should be made in the context of specific impacts questions (IPCC, 2013, p. 1086). It is known that global climate change affects a variety of factors associated with drought. There is high confidence that increased temperatures will lead to more precipitation falling as rain rather than snow (that change the river streamflow), earlier snowmelt, and increased evaporation and transpiration. But there is low confidence in the magnitude of future impact. Low precipitation and timing of water availability can cause, for example, agricultural drought, when available water supplies are not able to meet crop water demands. For instance, earlier snowmelt may not change the total quantity of water available but can lead to earlier runoff that is out of phase with peak water demand in summer. These are the impacts of changing precipitation in water system.

However, the modification of precipitation's layout provokes also other variations in water systems. Ocean regions of high salinity, where evaporation dominates precipitation, have become more saline, while ocean regions of low salinity, where precipitation dominates, have become fresher since the 1950s (IPCC, 2013, p.8). These regional trends in ocean salinity provide indirect evidence that evaporation and precipitation have changed, and that they will modify aspects of the water system. These trends could be observed also in other regions and water elements as watercourses and lakes. In the report *Salinity in the Casamance estuary. Occurrence and consequences* (Blesgraaf et al., 2006) the authors report that since the late 60s the rainfall got lower compared with the years before. The period of lower rainfall lasted for some years, known also as the Sahelian drought. In this period the estuary has become hypersaline (due to evaporation and lower rainfall the salinity of estuary water exceeds the ocean salinity), and the conclusion that can be made from the authors' model is that hyper salinity is more or less irreversible. Agriculture and fishery suffer much from high salinities and the ecosystem is far from different. Freshwater is scarcer here, since rainfall is often less than in the downstream lowlands, thus making the condition for agriculture less favorable. So water use for several purposes and water management have become very difficult in this region.

2.3.2 Impacts on energy resources

Energy resources are generally defined as whatever that can be used as a source of energy. Another definition could be the sources from which electricity or other forms of energy generation can be drawn.

There are lots of different kind of energy resources, and they fall into two main categories: renewable energy sources, as wind, solar, biofuels and water, and nonrenewable energy sources, as oil, natural gas and coal. All energy resources that exist in nature could be affected by climate change (in different ways): in this section we refer to impacts to energy endowment, which concerns the amount of primary energy available. Renewable energy resources are fluxes of energy, and their endowment is closely related to climate parameters and changes. On the other hand, fossil fuels are stock sources, thus climate change influences the access to them and not their endowment.

All the resources are affected by all the outcomes of climate change. Consequently, we aggregate the climatic consequences under a unique parameter, defining climate change as the unique cause of endowment affliction. Then, we evaluate water as an independent origin of impacts, which affects only a particular energy source, the hydropower one. Hydropower endowment is affected by climate change and its consequences as other resources, so we may consider it modified by the unique parameter climate change. But, as already stated, we consider water as part of energy resources and also as an independent and important system, which has a strong correlation with the energy system. And, as energy system and energy resource in general, it is influenced by all climate change consequences, as we have explained earlier. On account of this, here we emphasize the strong and direct correlation between water and energy systems, which can be observed in energy endowment, demand and supply, highlighting that a modification of water system originates an alteration of hydropower endowment.

Figure 2.5 summarizes the particular afflicted areas.

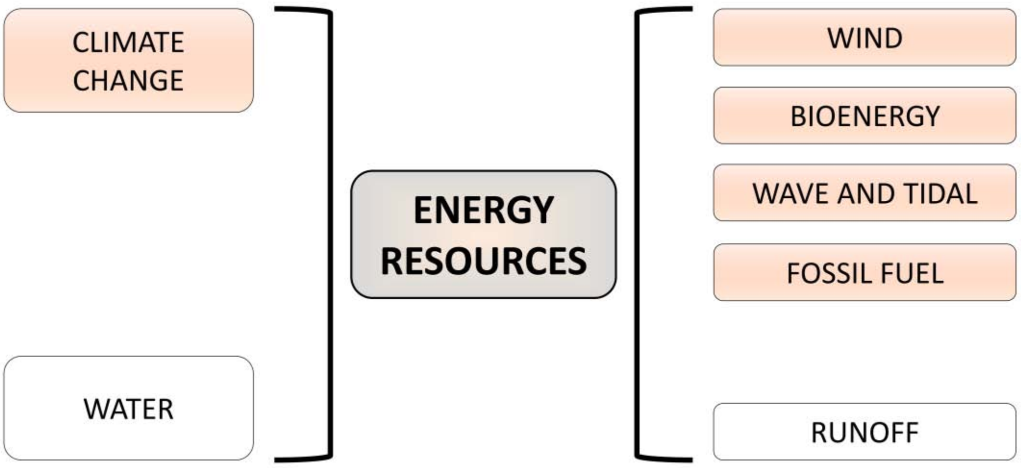

Figure 2.5 Climate change's impacts on energy resources. Created by author

Climate change

As just mentioned, this subdivision deals with impacts of climate change on all energy resources except for hydropower one. The contemplated renewable resources are wind energy, liquid biofuels, wave and tidal energy, while are oil, natural gas and coal for non-renewable resources.

Leaving aside the physical aspects that generate winds, we focus on the aspects of climate change which affect the wind energy endowment.

The availability and reliability of wind power depend on weather and climate conditions. The main mechanism by which global climate change impacts wind energy endowment, is the shifts in geographical distribution and variability of wind speed (inter- and intra-annual variability) (Schaeffer et al., 2012). Recent findings suggest that climate change may introduce this risk on wind power generation. Carbon dioxide emissions from fossil fuel consumption are contributing to global warming and are projected to have dramatic impacts on global climate on decade to century timescales. These impacts will affect the statistics (maximum, minimum, mean and variance) of all meteorological variables, including wind. (Breslow and Sailor, 2002).

We must consider another aspect that will affect wind energy. The amount of energy that wind transfers to a wind turbine depends on the wind speed, the area of the turbine's rotor and the density of the air. The effect of air density on energy density is modest but not negligible (Pryor and Barthelmie, 2010). An increase in air temperature leads to a decrease of air density with a commensurate decline in energy density.

Liquid biofuels are vulnerable to the effects of weather modifications on crops used as raw materials to produce ethanol and biodiesel (or other biofuels). Some impacts of climate change on agriculture can be the changes in temperature and rainfall patterns, in the frequency of precipitation and extreme events, in the level of carbon dioxide. As well summarized by Schaeffer et al. in *Energy sector vulnerability to climate change: a review* (Schaeffer et al., 2012), climate change directly affects many key factors of agriculture, like crop yield, agricultural distribution zones, incidence of pests and the availability of lands suitable for growing some crops:

- Temperature increases can modify soil conditions (water, carbon, nitrogen) and impact crop fertility and productivity levels;
- Higher CO_2 levels can cause a positive impact by improving photosynthesis;
- Alteration in regional temperature variations causes a modification in regional agriculture profiles because each plant has a temperature range suitable for his growth;
- Rising temperature leads to a higher rate of evapotranspiration in plants and reduces productivity;
- Temperature increases can affect the metabolism of insects increasing the incidence of pests;
- Extreme climate conditions (droughts, frosts, fires, storms) can affect crops in general.

In terms of resource endowments, the main impact is related to eventual losses in suitable areas for growing energy crops due to modifications in climate.

The World Bank Study *Climate impacts on energy systems: key issues for energy sector adaptation* (Ebinger and World Bank, 2011) talks about the several ways in which the ocean can provide energy. Wave energy is the most commonly used ocean energy worldwide, although it is still not developed or disseminated to the same extent as other renewable energy resources. And tidal energy is another kind of ocean energy.

Climate change impacts on wind energy have direct impacts on wave formation. Wind climate effects and wave generation have a nonlinear relationship and show different long-term trends around the globe. In some regions a positive impact on wave energy with an increasing trend in wave height has been observed. In other regions, there has been an opposite trend, with a negative impact on wave energy owning to a decrease in wave height.

In closing, no references have been found on climate change effects on tidal energy. It is possible that sea level rise could alter tidal basins and affect the tidal range. Tidal currents may also change as a result of sea level rise.

Although climate change does not impact the actual amount of existing oil, natural gas and coal resources, it can affect our knowledge about these resources and the access to them (as mentioned above). For example, climate change may facilitate access to several areas by diminishing the ice cover in the Arctic region. Ice-free summers can increase the length of drilling seasons, which can affect the rate at which new fields can be developed, so oil and gas reserves and resources could be affected positively by new climate conditions (Schaeffer et al., 2012). Coal quality – and so coal endowment – could be affected positively or negatively by new climate conditions, depending on the increasing or decreasing of average precipitation.

Water

In the introduction of this paragraph it is asserted that we evaluate water as an independent origin of impacts to energy system due to climate change. In particular, it mostly influences the hydropower endowment in the energy resource sector.

Assessing all the impacts of climate change on hydropower endowment is not simple. There are several factors that influence the availability of water resources for hydropower plants. Hydropower generation depends directly on the availability of water resources and the hydrological cycle. Hydropower endowments are a result of the excess water that turns into runoff. According to IPCC, runoff is that part of precipitation that does not evaporate and is not transpired, but flows over the ground surface and returns to water bodies (IPCC, 2013, p. 1461).

A variety of hydrological models have been used to evaluate the impacts that climate change can have on runoff. They use, basically, precipitation and temperature projections from General Circulation Models (GCM) or hypothetical scenarios (e.g. (Arnell, 2004)): essentially they translate the climate variables into runoff. The hydropower endowment depends on the seasonal pattern of the hydrological cycle. In regions where snowmelt is a relevant factor in the annual water cycle, climate change may cause impacts to runoff. This issue can be particularly relevant where the glaciers can be affected by higher temperatures (Schaeffer et al., 2012). Temperature modifies also the saturation vapor pressure of water in the air: an higher temperature implies an increasing evapotranspiration and a reduction of runoff (Milly et al., 2005). Another factor that could influence water resource is the regional changes in water demand due to changes in population and economic activities (especially irrigation demand for agriculture).

2.3.3 Impacts on energy demand

As the climate of the world warms, the consumption of energy in climate-sensitive sectors is likely to change. Possible effects include:

- Decreases in the amount of energy consumed in residential, commercial, and industrial buildings for space heating and increases for space cooling;

- Decreases in energy used directly in certain processes such as residential, commercial, and industrial water heating, and increasing in energy used for residential and commercial refrigeration and industrial process cooling (e.g., in thermal power plants or steel mills);
- Increases in energy used to supply other resources for climate-sensitive processes, such as pumping water for irrigated agriculture and municipal uses;
- Changes in the balance of energy use among delivery forms and fuel types, as between electricity used for air conditioning and natural gas used for heating;
- Changes in energy consumption in key-sensitive sectors of the economy, such as transportation, construction, agriculture and others (Wilbanks et al., 2008, p. 7).

This section summarizes the potential effects of climate change on energy demand. It mainly focuses on the effects of climate change on energy consumption in buildings (emphasizing space heating and space cooling), in industry and in agriculture. We may say that this section focuses the attention on the impacts on primary, secondary and tertiary economy sectors.

Energy demand is influenced by climate change and in particular by temperature changes. A rise of temperatures implies, for example, a decrease of energy consumption in winter for space heating and an increase in summer for space cooling. Temperature variation affects also the industrial and agriculture sectors. Industrial energy demand is particularly sensitive to climate change and especially to the rise of air temperature. In the agriculture sector climate change can affect water and electricity demand for irrigation purposes. Finally, an alteration of water source properties, as temperature or availability, causes a change in energy demand and use.

Hence, we could indicate that climate change modifies energy demand through temperature changes and water changes. This comment is summarized in Figure 2.6.

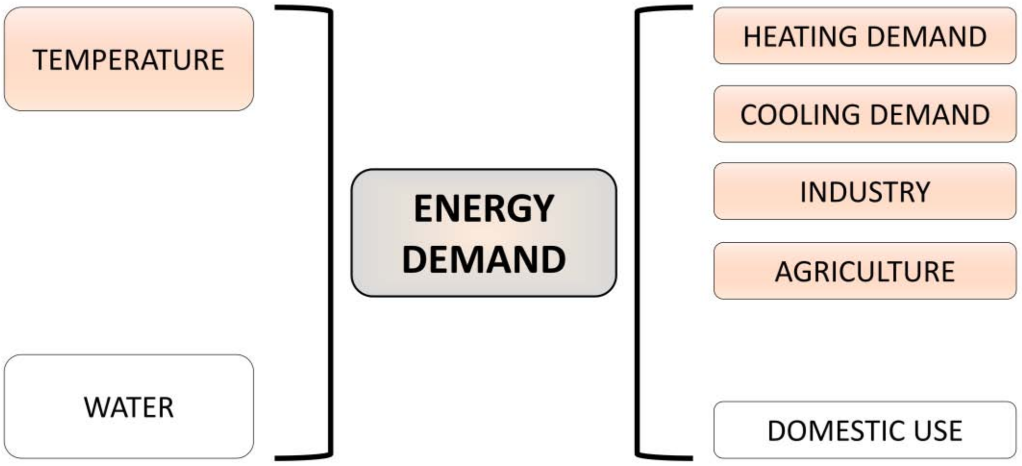

Figure 2.6 Climate change's impacts on energy demand. Created by author

Temperature

We can notice different effects of temperature change in the demand side: the most evident is that higher temperatures imply lower demand for heating and higher demand for cooling. The performance of motors and engines can vary with temperature. Furthermore, due to temperature rising, water and energy demand can vary in industries and agriculture.

The most assessed impact on energy demand is the estimation of future heating and cooling due to temperature changes. The first studies on this subject date from the last 1980s. They concerned the calculation of energy demand for heating (winter) and cooling (summer) in some specific regions, or the estimation of changes in consumption and peak load. Anyway, some empirical studies have found that total energy demand depends on outdoor temperature in a U-shaped fashion: at low temperature there is a relatively high energy demand (for heating), at intermediate temperatures the energy demand tend to be lower (no need for heating or cooling), high temperatures tend to increase energy demand (for cooling) (see Figure 2.7). This U-shaped temperature dependence pattern (TDP) suggests that climate change may have ambiguous consequences for future energy demand at the global level, as increasing outdoor temperatures could generally reduce heating demand while increasing cooling demand. This kind of analysis is usually studied using the concept of heating and cooling degree days.

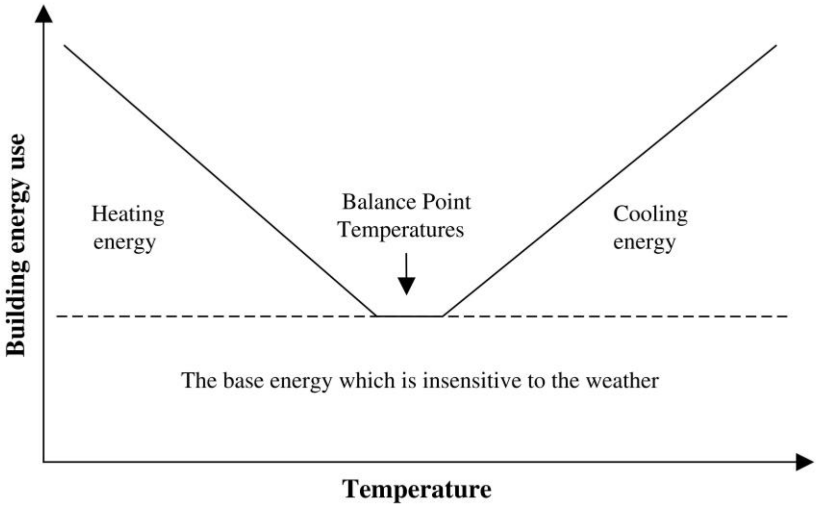

Figure 2.7 The relationship between building energy use and the outdoor temperature (Guan, 2009, p. 794)

Industrial energy demand is not particularly sensitive to climate change (Scott and Huang, 2007, cited in Ebinger and World Bank, 2011). The temperature differences that are covered in industrial processes are often much larger than outdoor temperature fluctuations. Many continuous processes operate at relatively stable surrounding temperatures and, thus, have a relatively stable demand. However, continuous processes related to food processing and storage, for example, have relatively small temperature differences to bridge and are possibly more sensitive to outdoor temperature variations (especially since these cooling processes often exchange heat with the outdoor air). Furthermore, industrial use of water will vary with climate change: projections are given, for example, by the MIT Joint Program on the Science and Policy of Global Change in its *2014 Energy and climate outlook* (MIT Joint Program on the Science and Policy of Global Change, 2014).

Agricultural energy use falls into five main categories: equipment operations, irrigation pumping, embodied energy in fertilizers and chemicals, product transport, drying and processing. A warmer climate might lead to a rising demand for water and irrigation, and therefore increase the use of energy for pumping. However, no accurate estimates of these effects could be found in available literature.

Water

The rise of temperatures and the change of precipitation patterns produce regional and seasonal changes in water cycle. These modifications could lead to an alteration of energy demand in final use. In some regions across the world there are already problems related to the availability of freshwater resources for domestic use.

2.3.4 Impacts on energy supply

Whatever is able to convert primary energy into a form that can be used by consumers is considered as a technology which belongs to energy supply system. In this study we take in consideration electricity as kind of energy used by consumers. Consequently, in this segment we examine those technologies which convert primary resources (in the form of stock or flux energy) into electricity and those technologies and facilities correlated with electricity generation. Therefore, we point the attention on the facilities which generate electricity, as hydropower, nuclear power plants, photovoltaic panels and wind farms and on the infrastructures correlated to electricity generation, as refining plants, pipelines and electricity grid.

Energy transformation facilities can be influenced by climate change in a variety of ways, affecting the system's capacity to supply energy to consumers and meet specific energy services. Great changes of global climate should happen in the near and long term. Global climate change is already occurring, but the greatest changes will be in the future, as impacts on energy system and energy facilities. Most of the facilities which are now in operation will be still operating in the middle and long term, when the new climate conditions occur (such as hydropower plants). So, climate impacts analyses must take into account a major share of the current energy system and also the energy facilities under construction or planned to be built in the next few years. Instead the analysis of short lifespan technologies implies in assuming that the facilities would be replaced over time by similar technologies at the same location: for some technologies, where there is still some room for advances or relocation, climate impacts can be overestimated.

Climate change as a whole alters the energy supply and the facilities that constitute an energy system. Thus, all the impacts should be attributed to climate change. But, as we saw in Figure 2.1, we consider that more entities afflict the energy supply. This is due to the fact that during the analysis we have pointed the attention on some peculiarities of the facilities which supply electricity. The energy-natural system causes alterations on energy production in specific ways. Air temperature, for example, weighs on the efficiency of photovoltaic cells and thermal power plants. Water temperature bears upon the refrigeration system of power plants and this fact affects water withdrawal and water consumption. Thus, the links between energy supply and temperature and water indicate these particular correlations between energy generation and natural environment.

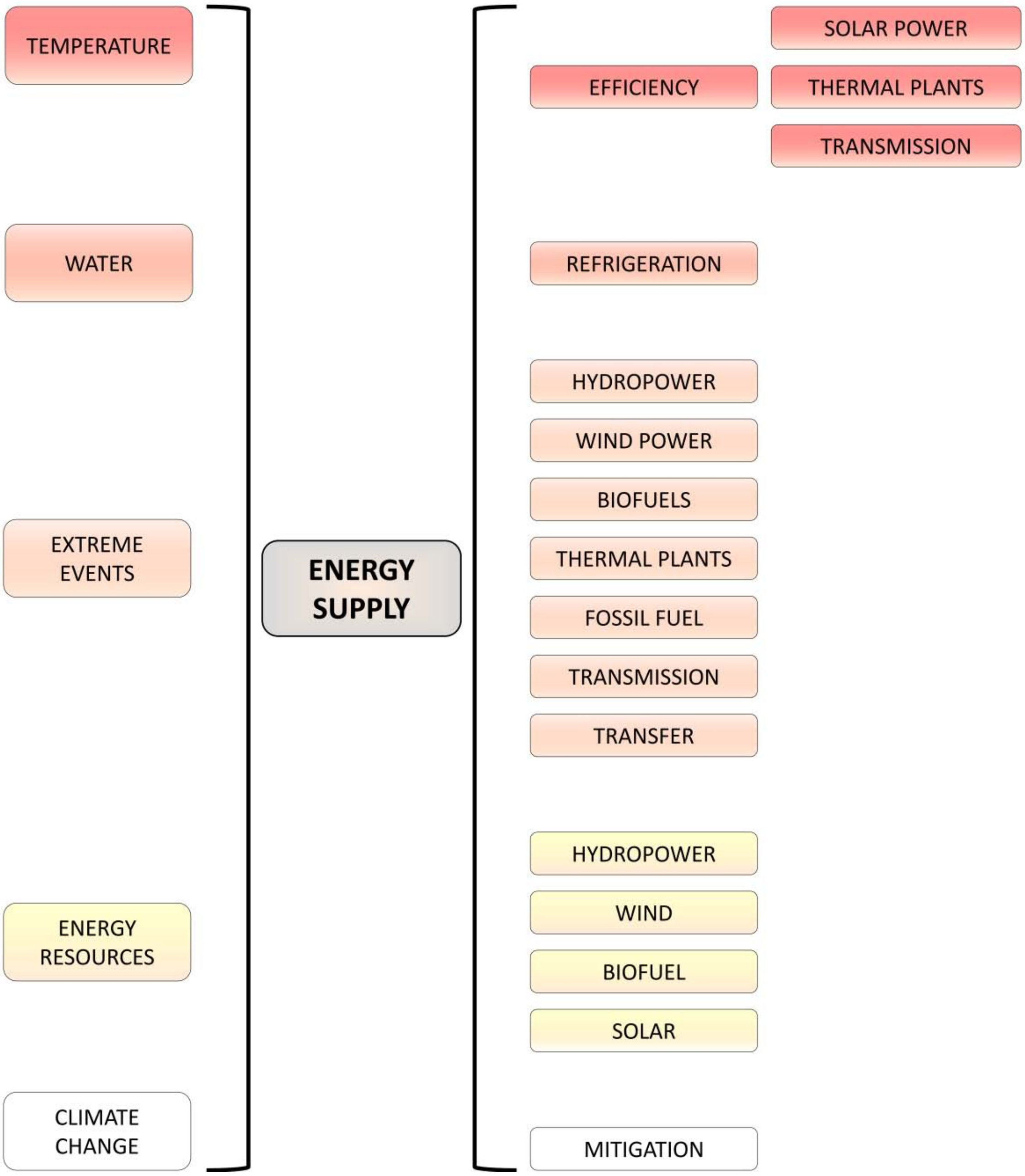

Figure 2.8 Climate change's impacts on energy supply. Created by author

Therefore, the next description is structured in a specific way. Firstly, there will be an explanation of the influences of temperature and water on energy supply system. Then, there will be an account of the impacts of energy resources and extreme events on the supply structure. And finally we will give a hint of the adjustment of the share of particular electricity supply technologies which will be necessary to respect the established mitigation targets. This structure is portrayed in Figure 2.8.

Temperature

The temperature of the air influences the efficiency of energy generation installations as photovoltaic panels and thermal plants, and the efficiency of the transmission, distribution and transfer system.

Photovoltaic cells suffer from increasing air temperatures. The energy produced by PV cells depends on the cell temperature: an increment of cell temperature due to a rise of air temperature reduces the PV electric generation.

The thermal power plant denomination includes several kind of generation technologies, which use different fuels to get the electricity output. These technologies use coal, natural gas, nuclear, geothermal, solar and biomass energy residues to obtain electricity utilizing two different thermal power cycles: the Rankine cycle and the Brayton-Joule cycle. These plants need a heating and a cooling system, which are the most affected components of a power plant. The average ambient conditions like temperature, pressure, humidity and water availability influence the cycles and the supply of energy. In this subsection the analysis concentrates on air temperature and the consequent efficiency of the plant.

In a Rankine cycle based plant the heat from fuels is used to produce high-pressure steam, which is expanded over a turbine to produce electricity. The driving force for the process is the phase change of the steam to a liquid which follows the turbine (it is realized in a condenser), from which arises the demand for cooling water. A vacuum is created in the condensation process that draws the steam over the turbine. This low pressure is critical to the thermodynamic efficiency of the process. Increased backpressure will lower the efficiency of the generation process. Increases in ambient air temperatures and cooling water temperatures will rise steam condensate temperatures and turbine backpressure, reducing power generation efficiency (U.S. Department of Energy, 2013, pag. 10).

In *The impact of climate change on the electricity market: a* review (Mideksa and Kallbekken, 2010) the authors explain that how efficient is a plant in transforming fuels into electric power depends upon the temperature differential between the machine and the external environment. The higher is the heat differential, the higher is the efficiency of conversion and vice-versa. As climate change is likely to produce higher air temperatures, the heat differential between the machine and the environment will decrease, thus reducing the net power generated from a given amount of fuel.

The electricity transmission system is as well affected by the rise of temperatures. Power lines suffer electricity losses due to higher temperature of the air and to the resistance it induces on the lines.

Water

Thermal power plants require significant amounts of water for refrigeration, making them vulnerable to fluctuations in water supply. For example, each kilowatt-Hour (kWh) of US thermoelectric generation requires the withdrawal of approximately 25 gallons (nearly 100 liters) of water, weighted-average for all thermoelectric power generation (Feeley et al., 2008). Per unit of energy produced, thermal power plants are the energy sector's most intensive users of water.

In Chapter 17, *Water for energy,* of *World energy outlook* 2012 (IEA, 2012) the authors highlight that in future scenarios the trends will be to shift towards higher efficiency power plants, with more advanced cooling systems that reduce withdrawals but increase consumption of water per unit of electricity produced. Cooling systems will move from once-through systems (which withdraw freshwater, pass it through a steam condenser to absorb heat and return it at higher temperature to a nearby water body) to wet re-circulating systems (which withdraw freshwater and pass it through a steam condenser but instead of being discharged downstream, the heated water is cooled in a wet tower) and dry cooling systems (which use air flow through a cooling water tower to condense steam).

Projected changes in water availability around the world, point to a lower availability of water in some regions. It can be expected, therefore, that power plants will increasingly compete with other water users (like agriculture and public supply) in water-stressed areas.

Extreme events

Extreme events could affect all type of power generation supply and related infrastructure. They could influence thermal and nuclear plants, hydropower plants, wind farms, biofuels productivity, oil and gas supply facilities, oil and gas pipelines, electricity grid and infrastructure in general. Energy supply system is subject to several impacts which may cause interruptions of electricity power supply.

Observed and projected increases in a variety of extreme events like hurricanes, will have a significant impact on the energy sector in general. Hurricanes, with their strong winds and high waves, can have a debilitating impact on energy supply. But extreme events are not restricted to hurricanes. Extreme warm days, cold days and precipitation, droughts and floods belong to this category of weather events.

Extreme temperatures for example afflict different kind of energy productions. The most stressed technologies are thermal power plants, oil and gas platforms and electricity grids. Kopytko and Perkins in *Climate change, nuclear power, and the adaptation-mitigation dilemma* (Kopytko and Perkins, 2011) concentrated their studies on nuclear power plants, focusing the attention on inland sites in France and coastal sites in USA. In France, warmer than average summers from 2003 to 2006, required extensive operational changes to maintain a steady power supply from nuclear power plants. Blackouts were avoided in France by exercising several options including the purchase of energy on the wholesale power market, the conservation of energy by citizens, the negotiations of lower loads from industry consumers and the reduction of exports to Italy. And also, Italy relies on France for much of its power supply. In 2003, Italy purchased 35.2% of its energy imports from France and consequently many Italian cities experienced blackouts lasting several hours.

In *The impact of climate change on the electricity market: a review* (Mideksa and Kallbekken, 2010) the authors concentrated on the efficiency of plants that depends on temperature differential between the machine and the external environment. They reported the words of the Associated Press on January 23, 2008: “During Europe’s brutal 2006 heat wave, French, Spanish and German utilities were forced to shut down some of their nuclear plants and reduce power at others because of low water levels – some for as much as a week.” (“Drought could shut down nuclear power plants,” n.d.).

Burkett in *Global climate change implication for coastal and offshore oil and gas development* (Burkett, 2011) highlighted that warming atmospheric temperatures can have string effects on OCS (Outer Continental Shelf) and resource development in the Arctic. Decreasing sea ice cover may require design changes to counter effects of increased wave action and storm surges. The author also stressed that warming atmospheric temperatures can have various effects on the resource development in the Arctic. Decreasing ice cover may require design changes to counter effects of increased wave action and storm surges like erosion. However, the biggest problem may be the thawing of the permafrost. Permafrost, an essentially permanently frozen land, acts as a concrete foundation for all the infrastructures in cold climates. As temperatures rise, the permafrost thaw. The ice trapped inside the frozen ground liquefies. If there is poor drainage, the water sits on the earth’s surface and floods. If there is good drainage, the water runs off, potentially causing erosion and landslides.

In their above mentioned paper Mideksa and Kallebekken treated also the problems associated to transmission lines. They reported a study by Eskeland et al. (*The future of European electricity: choices before 2020*, 2008) in which is stated that there could be an electricity loss in transmission due to higher temperature and the resistance it induces on power lines. Then, as reported in *U.S. energy sector vulnerabilities to climate change and extreme* weather (U.S. Department of Energy, 2013) increasing temperatures are expected to extend transmission losses, reduce current carrying capacity and increase stresses on the distribution system. The efficiency of the lines is reduced by higher temperatures. Another effect of the increasing temperatures – the thermal expansion – could produce a significant increase in sag, which could cause several problems. The transmission lines suffer from high temperatures, but also the electric power transformers are affected with them. Transformers could even fail causing interruptions of the electric power supply.

Droughts and floods can be associated to extreme precipitations. These variables significantly change the supply of electricity in the energy sector. Mideksa and Kallbekken (Mideksa and Kallbekken, 2010) commented that climate change affects hydropower production through the frequency of erratic river flow and hence dam safety. Most current dams are built without taking into account the possible impact of climate change and may have lower reservoir capacity to handle frequent extreme events, associated with river flow and snow melt. To the extent that climate changes occur abruptly, the dam safety issue becomes relatively more important. If the changes take place slowly over time, the dam safety issue becomes relatively less important.

Liquid biofuels then could highly be distressed. Frequency of extreme events like droughts and frosts modifies crop yields. Lower water availability caused by increased evapotranspiration due to rising temperatures and/or lower precipitation levels can reduce crop productivity.

Furthermore, Kopytko and Perkins (Kopytko and Perkins, 2011) in their paper investigated the impacts of inland floods on French nuclear power plants. The 1999 flood of Le Blayais revealed that flood protection had to be investigated and improved at many sites. The flooding event resulted from a high tide, wind speeds of 100 km/h and storm surge. The three units operating when the storm arrived shut down due to loss of off-site power.

Oil and gas production may be affected by structural damage caused by extreme events like flooding from sea level rise and storm surges that may lead to erosion and other damages.

Oil refining is also a large water consumption activity and can, thus, be affected by a lower water availability induced by climate change. Burkett in its *Global climate change implication for coastal and offshore oil and gas development* (Burkett, 2011) summarized other 5 climate change variables that are likely to affect oil and gas development in addition to increased atmospheric and ocean temperatures. These are changes in precipitation patterns and runoff, sea level rise, more intense storm, changes in wave regime and increase in carbon dioxide levels and ocean acidity. For example, extreme rainfall events that flood low-lying coastal sites, may damage onshore support facilities.

Also, fuel transport could be impacted by water. Decreased water levels in rivers and ports can cause interruptions, delays and increased costs in barge and other fuel delivery transportation routes. And, in addition, extreme events like floods could affect the transport. Increasing intensity and frequency of flooding increments the risk to rail and barge transport of crude oil, petroleum products and coal (U.S. Department of Energy, 2013).

Hurricanes distress all kinds of supply facilities. Extreme wind speeds and precipitations produce storm surges and floods in the areas affected by hurricanes. Windmills can operate only up to wind speeds of around 25 m/s: at higher wind speeds the strain on the turbine would be too high.

Nuclear power plants are highly damaged by hurricanes. Kopytko and Perkins studied the operation of US nuclear power plants during hurricane season. Hurricane Andrew in 1992 caused damage to a number of non-safety structures and equipment at Turkey Point. That event demonstrated the need to both design non-safety structures and equipment to withstand the postulated events, or assure that the consequence of their failure would not disable the safety function of safety-related structures, systems and components. The authors of the report in addition highlighted that while shutdowns during storms tend to be only days, the change to normal operating procedures that occur when sirens, communication, off-site power and site access are lost or restricted, alone or in combination, becomes problematic, and the restarting periods need to be shorter.

In *Energy sector vulnerabilities to climate change: a review* (Schaeffer et al., 2012) the authors reported that oil and gas supply from offshore and coastal low-lying facilities can be disrupted by extreme weather events, such as intense hurricanes. Hurricanes in the Gulf of Mexico in 2004 and 2005 resulted in a large number of damaged and destroyed offshore oil and gas structures: over 115 platforms were destroyed and more than 52 structures were extensively damaged. Finally, energy distribution might be impacted by weather events. For instance, high winds can damage to distribution network and lead to energy interruptions.

Energy resources

Energy resources need to be converted into final energy sources in order to meet specific energy services. Energy transformation facilities can be affected by climate change in a variety of ways, affecting the system's capacity to supply energy to consumers. But, as we have seen, climate change alters the properties and availability of energy resources, which, as a result, affect the energy supply system.

The amount of electricity that can be generated from hydropower plants depends not only on the installed generation capacity, but also on the variation in water inflows to the power plants' reservoirs. Natural climate variability has already great influence on the planning and operations of hydropower systems. Changing climate conditions may affect the operation of the existing hydropower system and even compromise the variability of new investments. The methodological approach normally used to assess climate impacts on hydropower generation uses climate change simulated river flows in an electric power model. A hydrological model is used to convert the impact of climate change into water inflows to the reservoirs of hydropower plants. An electricity power model is then used to convert hydrological impact into variations in electricity production. The models used to assess climate impacts depend on the complexity of the system. Two factors especially influence an hydropower generation system (de Lucena et al., 2009).

- *The penetration of hydro generation on electricity system* (whether hydroelectricity is complementary or complemented by other power sources). If it is complementary to other generating sources, the average values of hydropower production provide a good measure of impact (most of the electricity is produced by other sources, so the maximum impact that I can have from hydro generation is the whole hydroelectricity power generation). If it is complemented by other generating sources, in practice if the electric system is based fundamentally on hydropower, the risk of power shortages must be minimized. Thus the measure of impact must be assessed in terms of firm power[1]. In some extreme cases the worst historical hydrological conditions are used to assess the firm power.
- *The geographical dispersion and the level of integration through transmission capacity*. Transmission may play an important role in coping with regional climate variations in interconnected power systems that cover a vast area.

Individual plant characteristics also influence the vulnerability of hydropower system to climate change, especially in small systems where there are small run-of-river plants. These plants offer little operational flexibility. Natural river flow can be highly variable, across seasons and years. So reservoir storage capacity can compensate these variations in water inflow.

The paper *The vulnerability of energy infrastructure to environmental change* (Paskal, 2009) aims to identify some of the most susceptible nodes in the global energy infrastructure. It focuses on hydropower generation, distinguishing clearly the impacts of two different kind of hydropower power plants, the primarily glacier-dependent and the primarily precipitation-dependent.

Glacier-dependent hydro plants are those hydroelectric installations that depend primarily on glacial thaw, such as some in the Himalayas, Alps and Andes. These installations are likely to face difficulties in managing widely varying flows both seasonally and over yeas. In Europe for example, mountain areas are likely to see more flooding in winter and spring, and drier summers. These fluctuations can disrupt hydroelectric power generation, erode infrastructure and damage valuable regional industries. Currently many glaciers are retreating, producing more runoff than dams were designed for. Snowpack normally act as a natural reservoir during winter, but climate change will modify this attribute. One immediate

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[1] Firm power: the amount of energy that hydropower system can produce under critical conditions, defined by the level of reliability expected from the entire system.

impact of the thaw is flooding. Once the glaciers reach a minimal extent, the flow may markedly decline, creating a new set of challenges, including a potential decline in hydroelectric production.

Precipitation-dependent hydro plants are those installations that depend primarily on predictable seasonal precipitation. They will find it increasingly difficult to anticipate flow. This could potentially cause a decline in power generation, floods and irrigation problems. Unexpected rainfall has already complicated the management of some dams. Them often serve three purposes: flood control, irrigation and power generation. Most rain-dependent plants are designed to store water from the rainy season in order to be able to irrigate and generate power in the dry season. Those plans rely on predictable rain patterns. If precipitations are inadequate, there will be a loss in generation. The situation can be equally problematic when there is too much water for the design of the installation. If the reservoir fills in the rainy season and then, owing to changing precipitation patterns, the rain keeps falling well into what should be the dry season, the reservoir can back up and impart problems to the upstream zone. If in order to prevent any damage upstream a higher quantity of water is added to the already swollen river, the downstream zones could be flooded and furthermore a certain amount of stored energy would be wasted.

Another factor which affect the hydropower generation is the Glacial Lake Outburst Flooding (GLOF). GLOF events occurred in areas where there are lots of glaciers, like in Nepal. Climate change and higher temperatures are contributing to a very rapid increase in the volume of glacial lakes, which significantly increases the probability of catastrophic events (Agrawala et al., 2003, p. 31).

Wind energy cannot be naturally stored. The natural hourly, daily or seasonal variability of wind speeds has a significant impact in the energy produced from wind turbines. Power demand fluctuations may not match natural variations in wind speeds, rendering the operation of wind power more susceptible to changing wind patterns resulting from climate change. The energy contained in wind is proportional to the cube of wind speed, which means that alterations in the later can have significant impacts on the former. Wind speeds below the average yield much less power, while speeds much above the average can overstress turbine components and activate the cut-out speed control. This implies that the analysis of climate impacts on wind energy supply must be done using the frequency distribution of wind speeds, not only average values. Alterations in wind speed frequency distribution can affect the optimal match between the energy availability from the natural resource and the power curve of wind turbines. However, future climate projections have serious limitations in reproducing wind speeds and their frequency distributions or directional changes.

Solar energy generation is affected by increasing air temperature, which modifies the efficiency of photovoltaic cells. But in addition to air temperature, also a change in global radiation revises the electricity output of solar cells. Fidje and Martinsen in their article *Effects of climate change on the utilization of solar cells in the Nordic region* (Fidje and Martinsen, 2006) explained the results of their experiment on PV panels. The effect of climate change on PV systems had been investigated using the IPCC scenarios A2 and B2 for the period 2071-2100. Both scenarios show reduced global solar radiation and increased temperature.

Liquid biofuels production is vulnerable to impacts of climate change on crop production. Modification of regional temperature, precipitation, frequency of extreme events and suitable lands affect crop yield and consequently liquid biofuels generation. Thus effects on biofuels production are directly correlated to climate change impacts on crop production: impacts that increase crop productivity raise also biofuels production, impacts that decrease crop productivity instead reduce biofuels production.

Mitigation of climate change

In this specific section the focus is not on those changing parameters which all together affect energy supply: in this section the attention is addressed to mitigation. Other specific parameters that have an influence on energy supply have already been evaluated. We use the connection between climate change and energy supply to place mitigation on the impacts analysis.

Adaptation and mitigation are two different techniques to battle climate change in the energy sector. The conventional view is that adaptation and mitigation are incompatible: in reality one doesn’t exclude the other. These two methods can work together optimally and give benefits one to the other. Implementing mitigation targets helps to adapt in an easier way all energy systems and in particular the supply sector.

Mitigation is a human intervention to reduce the sources or enhance the sinks of greenhouse gases (Intergovernmental Panel on Climate Change et al., 2015, p. 4). Mitigation, together with adaptation to climate change, contributes to the objective expressed in Article 2 of the United Nations Framework Convention on Climate Change (UNFCC):

> The ultimate objective of this Convention and any related legal instruments that the Conference of the Parties may adopt is to achieve, in accordance with the relevant provisions of the Convention, stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Such a level should be achieved within a time frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner. (United Nations, 1992)

A broad range of sectoral mitigation options is available and it can reduce GHG emission intensity. Only with the implementation of these strategies we can achieve low-stabilization levels of CO_2 in the atmosphere. For example, decarbonizing (i.e. reducing the carbon intensity of) electricity generation is a key component of cost-effective mitigation strategies. For reaching certain levels we must reduce GHG emissions, changing the structure of the electricity supply system.

Recently total anthropogenic GHG emissions have continued to increase, over 1970 to 2010, with larger absolute decadal increases toward the end of this period. CO_2 emissions from fossil fuels combustion and industrial processes contributed about 78% of the total GHG emission increase. Globally, economic and population growth continue to be the most important drivers of increases in CO_2 emissions from fossil fuel combustion. Without additional efforts to reduce GHG emissions beyond those in place today, emissions growth is expected to persist driven by growth in global population and economic activities. Baseline scenarios studied by IPCC, those without additional mitigation, result in global mean surface temperature increases in 2100 from 3.7°C to 4.8°C compared to pre-industrial levels.

In the following part of the analysis, in which the various future impacts of climate change are specifically examined, there is a comprehensive explanation of the actions we must undertake to change the electric supply system and reach the desired targets.

CHAPTER 3

FUTURE PROJECTIONS OF CLIMATE CHANGE'S IMPACTS ON ENERGY SYSTEMS

Near and long-term climate change and its impacts on weather variability (and extremes) will impact energy resources and their production and use, and they will affect strategies for adaptation. Some impacts may be systemic and affect large geographical area. Others may be localized and influence only specific infrastructures.

First of all, here we introduce the parameters and characteristics affected by climate change: temperature, precipitation, extreme events and water. We give an account of expected future projections of these peculiarities, basing on the last assessment of IPCC: *Climate change 2013. The physical science* basis (IPCC, 2013). IPCC provides a clear and up to date view of the current state of scientific knowledge about climate change in the Fifth Assessment. Almost all data and ranges reported in this chapter are pulled out from the IPCC study, unless it is otherwise stated. In AR5 IPCC described and showed two projections at different times: a near-term and a long-term climate prediction. They supplied these data both for climate parameters and for water. Thereafter, we conclude with all data and ranges about climate change on the energy system, specifically on energy resources, energy demand and energy supply. These data have not a specific projection period: all the trends and statistics are collected from several different studies available in literature, which could have distinct horizons of assessment.

The account of future climate impacts on natural and energy system is made with the help of a summary table of all the impacts (see Table 3.1), that follows the order described in the diagram of Figure 2.1 at page 34, and with the help of a series of tables which introduce and summarize the various sections of the account.

The portrait is divided in two parts: in the first one we illustrate climate change and its tendencies, whereas in the second one we define all the repercussions of climate change and its tendencies on the energy system, focusing specifically on the electric energy system. Every row of the summary table refers to a specific impact, and every row is expanded during the presentation to give more details than those already presented.

Table 3.1 is the result of the sum and the reduction of all the tables which introduce each section of the analysis. All the tables together may be useful to get an immediate quantitative overview of the various problems facing energy system, caused by climate change.

Table 3.1 Summary table of climate change and its impacts on the energy system

IMPACTS			PROJECTIONS / TRENDS		REFERENCE
			NEAR TERM PROJECTIONS: 2016 – 2035 REFERENCE PERIOD: 1986 - 2005	LONG TERM PROJECTIONS: 2081 – 2100	
CLIMATE CHANGE	TEMPERATURE	GMST	+0.47°C to +1.00°C (CMIP5, RCP4.5)	+0.3°C to +1.7°C (CMIP5, RCP2.6) +2.6°C to +4.8°C (CMIP5, RCP8.5)	(IPCC, 2013)
		OCEAN	Top 100m: warmer (CMIP5, all RCPs)	Top 100m: +1°C (RCP2.6) to +3°C (RCP8.5)	(IPCC, 2013)
	PRECIPITATION	PRECIPITATION PATTERN	-7% to +22% (CMIP5, RCP4.5)	+0.5 to 4%/°C (CMIP5, RCP2.6)	(IPCC, 2013)
	EXTREME EVENTS	TEMPERATURE	Annual warm days: 20-30% (CMIP5, RCP8.5) Annual cold days: 3.0-6.0% (CMIP5, RCP8.5)	Annual warm days: 55-70% (CMIP5, RCP8.5) Annual cold days: 0.5-1.0% (CMIP5, RCP8.5)	(IPCC, 2013)
		PRECIPITATION	Increase in heavy precipitation (CMIP5) Daily local extremes: +5 to 10%/°C of warming	+5% (RCP2.6) to +20% (RCP8.5)	(IPCC, 2013)
		ATMOSPHERIC CIRCULATION	Increase of North Atlantic hurricane intensity	Increase in the frequency of category 4-5 tropical cyclones in the North Atlantic and SW Pacific	(IPCC, 2013)
		SEA LEVEL	Increase of sea level extremes	Increase of sea level extremes	(IPCC, 2013)
WATER	CLIMATE CHANGE	CRYOSPHERE			
		• SEA ICE EXTENT	Nearly ice-free Arctic in Sep by 2037	NH: -8% (RCP2.6) to -34% (RCP8.5) in Feb NH: -43% (RCP2.6) to -94% (RCP8.5) in Sep SH: -16% (RCP2.6) to -67% (RCP8.5) in Feb SH: -8% (RCP2.6) to -30% (RCP8.5) in Sep	(IPCC, 2013)
		• SNOW COVER EXTENT	NH March to April average: -5.2%±1.9% (RCP2.6) to -6.0%±2.0% (RCP8.5)	NH March to April average: -7%±4% (RCP2.6) to -25%±8% (RCP8.5)	(IPCC, 2013)
		• PERMAFROST	Annual mean near-surface permafrost area: -21%±5% (RCP2.6) to -20%±5% (RCP8.5)	Annual mean near-surface permafrost area: -37%±11% (RCP2.6) to -81%±12% (RCP8.5)	(IPCC, 2013)
		EVAPORATION	Generally +1 to 3% for each degree of increase Increases over most of the oceans. Increases or decreases over land following the precipitation pattern over land		(IPCC, 2013)
	TEMPERATURE	SEA LEVEL	Projections: 2081 – 2100. Reference period: 1986 - 2005		
		• GLOBAL	0.40 [0.26 to 0.55] m (RCP2.6) to 0.63 [0.45 to 0.82] m (RCP8.5) (in the period 2081-2100)		(IPCC, 2013)
		• HEAT EXPANSION	0.14 [0.10 to 0.18] m (RCP2.6) to 0.27 [0.21 to 0.33] m (RCP8.5) (30 to 55% of the global projections)		(IPCC, 2013)
		• GLACIER MELTING	0.10 [0.04 to 0.16] m (RCP2.6) to 0.16 [0.09 to 0.23] m (RCP8.5) (15 to 35% of the global projections)		(IPCC, 2013)
	PRECIPITATION	FLOODS	No general global trend. Northern high latitudes: upward trend. Europa and Asia: upward, downward or no trend.		(IPCC, 2013)
		DROUGHTS	Low confidence on the magnitude of future impacts. Increases of meteorological droughts in the Mediterranean, Central America, Brazil, south Africa and Australia. Decreases in high northern latitudes.		(IPCC, 2013)
		STREAMFLOWS	General trend: decline in spring and summer streamflows and an increase in streamflows in winter		(California Climate Change Center, 2006)
		SALINITY	Sea Surface Salinity. Subtropical regions and Atlantic more saline. High latitudes and North Pacific less saline.		(IPCC, 2013)
ENERGY RESOURCES	CLIMATE CHANGE	WIND	"Winners" and "losers": regions where wind energy may benefit and regions where wind energy may be negatively impacted		(Pryor and Barthelmie, 2010)
			Reference period: 1964 - 2000 Northwest U.S. Wind speeds. Summertime: -5-10% (wind power resource: -40%). Wintertime: possible slightly increase		(Sailor et al., 2008)
			Reference period: 1948 - 1978 Continental U.S. Wind speeds. -1.0 to -3.2% in the next 50 years. -1.4 to -4.5% over the next 100 years		(Breslow and Sailor, 2002)
			Reference period: 1980 - 2000 Baltic sea region. Wind power potential: +15% Ireland. Wind power potential. Wintertime: +4-8%. Summertime: decrease UK. Wind speeds. Summertime: -5% (-15% in Northern Ireland). Wintertime: increases Eastern Mediterranean. Wind speeds. Increases over land and decreases over sea. Noticeable increase over the Aegean sea		(Mideksa and Kallbekken, 2010)
		BIOENERGY	Brazil. Projections: 2005-2030. Reference period: 1980-2000 Sugarcane. Planted are: +148%. Crop yield: +7% (from 77 to 82t/ha). Output: +161% Biodiesel. Shift of suitable growing zones for oilseed crops, from northeast to the south		(de Lucena et al., 2009b)
		WAVE AND TIDAL	Relationship wind – wave energy +20% in mean wind speed raises mean wave heights around 44%, and raises available power levels by 133% -20% in mean wind speed lowers available power levels by 67%		(Harrison and Wallace, 2005)
		FOSSIL FUELS	The access will be affected by climate change Coal. Precipitation increase: coal quality decrease, coal availability increase (no seam fires)		(Williamson et al., 2009)
	WATER	RUNOFF	Projections: 2050. Reference period: 1900 - 1970 +10-40% in eastern equatorial Africa, La Plata basin, high-latitude North America and Eurasia -10-30% in southern Africa, southern Europe, the Middle East, mid-latitude western North America		(Milly et al., 2005)
			From 44854 bmc (in 2010) to 52829 bmc (in 2100)		(MIT, 2014)
ENERGY DEMAND	TEMPERATURE	HEATING DEMAND	+0.8% a year between 2000 and 2030, and after slowly decrease. -34% worldwide by 2100		(Isaac and van Vuuren, 2009)
		COOLING DEMAND	From 1900 kWh (in 2000) to 4800 kWh (in 2100). +7% a year between 2020 and 2030. Then +1% a year to the end of the century +70% greater than projected demand without climate change		(Isaac and van Vuuren, 2009)
		INDUSTRY	U.S. energy consumption per unit of industrial production: +0.0127% per increase in 1 HDD or +0.0032% per increase of 1 CDD Annual basis: -6.2% energy demand (a saving of 0.0422 EJ)		(Wilbanks et al., 2008)
			Use of water: +45% from 763 bcm (2010) to 1098 bcm (2100)		(MIT, 2014)
		AGRICULTURE	-10% from 1551 bcm (2010) to 1389 bcm (2100)		(MIT, 2014)
			Water withdrawals (B2 scenario): from 2498 bcm (1995) to 2341 bcm (2025), to 2256 bcm (2055) and 2211 bcm (2075)		(Alcamo et al., 2007)
	WATER	DOMESTIC USE	+100% from 348 bcm (2010) to 698 bcm (2100)		(MIT, 2014)
ENERGY SUPPLY	TEMPERATURE	EFFICIENCY			
		• SOLAR POWER	The increase of air temperature can modify the efficiency of photovoltaic cells and ultimately reduce the PV electric generation		(Fidje and Martinsen, 2006)
		• THERMAL PLANTS	With +1°C: -0.8% nuclear power output. -0.6% coal and gas power output U.S.: -1% reduction in electricity generation means a drop in supply of 25 billion kWh		(Mideksa and Kallbekken, 2010)
		• TRANSMISSION	California power grid. -7-8% transmission line capacity and -2-4% substation capacity due to +5°C (2100)		(U.S. Department of Energy, 2013)
	WATER	REFRIGERATION	-0.45% power output due to +1°C		(Mideksa and Kallbekken, 2010)
			Between 2010 and 2035: water withdrawals: +20%; water consumption: +85%		(IEA, 2012)
	EXTREME EVENTS	HYDROPOWER	Affected by flooding. Shutting down of the turbine operation or (rare) destruction of power plants and/or dams		-
		WIND POWER	Stressed by extreme wind speeds (25m/s): the strain on the turbine will be too high, and it could provoke serious damages		-
		BIOFUELS	Reduction of productivity of the crops by droughts, frosts, extreme temperatures and precipitations Destruction of biofuels' production equipment by storms and cyclones		-
		THERMAL PLANTS	Inland reactors/plants. Subject to heat waves (reduction of power generation) and inland floods (damage of ancillary facilities) Coastal reactors/plants. Subject to the rise of sea level (inundation, erosion), instability of shorelines, storms, flooding		(Kopytko and Perkins, 2011)
		FOSSIL FUELS	Increase of production shutdowns to avoid life of environmental damage		(Burkett, 2011)
		TRANSMISSION	Disruption of infrastructure of the electricity grid by weather phenomena and permafrost thawing		-
		TRANSFER	Interruption of barge transport of crude oil, petroleum products and coal due to decreased water levels (droughts)		(U.S. Department of Energy, 2013)
	ENERGY RESOURCES	HYDROPOWER	U.S. Colorado River: -40% hydropower production by the middle of 21st century U.S. Central Valley: -10-12% hydropower production		(Mideksa and Kallbekken, 2010)
			+0.08% of total generation, +2.46 TWh from current generation, reaching 2931 TWh (2050)		(Hamududu and Killingtveit, 2012)
		WIND	Offshore wind farms around the North Sea: +3-9% due to increases in wind speeds		(Mideksa and Kallbekken, 2010)
			Continental U.S.:-30-40% of wind power generation due to -10-15% mean wind speeds		(Breslow and Sailor, 2002)
		BIOFUEL	The magnitude of energy generating from biofuels depends on the quantity of energy resource produced		-
		SOLAR	Projections: 2071-2100. Reference period: 1980-2000 -6% electricity output due to -2% solar radiation (2071-2100)		(Fidje and Martinsen, 2006)
	CLIMATE CHANGE	MITIGATION	-40-70% GHG emission in 2050 than 2010 to reach 450 ppm CO2eq by 2100 (+2°C relative to preindustrial level) -25-55% GHG emission in 2050 than 2010 to reach 500 ppm CO2eq by 2100 -5-45% GHG emission in 2050 than 2010 to reach 550 ppm CO2eq by 2100 To reach 450 ppm CO2eq by 2100: improvements in efficiency, tripling/quadrupling share of zero carbon energy supply by 2050		(IPCC, 2015)

Note. (-) means that there is no a specific document which refers to. GMST means Global Mean Surface air Temperature

3.1 Expected climate change, its major consequences and physical impacts

This section of the thesis is based almost exclusively on the work of the IPCC Working Group I for the Fifth Assessment Report (AR5) (IPCC, 2013). The IPCC Working Group I assesses the physical scientific aspects of the climate system and climate change. It reviews and assesses the most recent scientific, technical and socio-economic information produced worldwide relevant to the understanding of climate change.

For the IPCC AR5, the scientific community identified a set of four specific emission scenarios, the Representative Concentration Pathways (RCP), from the peer review literature. Projected trends and data of future climate change came out of the multi-model experiment Coupled Model Intercomparison Project Phase 5 (CMIP5), which used the RCPs as input scenarios. For this reason, the diversified projections which came out from the CMIP5 are distinguished from each other by referring to the input scenarios, the RCPs.

Climate change appears in many ways. It affects several different elements which belong to natural system, as atmosphere, water cycle, atmospheric circulation, oceans and cryosphere. The major signs are the increase of temperatures, the alteration of precipitation patterns and the change in frequency and magnitude of extreme events. Practically, the changes we notice in natural system are the manifestations of climate change.

3.1.1 Projected changes in temperature

Table 3.2 Projected climate change's impacts on temperature

IMPACT	NEAR TERM PROJECTIONS	LONG TERM PROJECTIONS	REFERENCE
GMST	• +0.47°C to +1.00°C (CMIP5, RCP4.5) • +0.39°C to +0.87°C (CMIP5, RCP4.5, ASK approach)	• +0.3°C to +1.7°C (CMIP5, RCP2.6) • +1.1°C to +2.6°C (CMIP5, RCP4.6) • +1.4°C to +3.1°C (CMIP5, RCP6.0) • +2.6°C to +4.8°C (CMIP5, RCP8.5)	(IPCC, 2013)
OCEAN	In the CMIP5 models under all RCPs forcing scenarios, globally average surface and near-surface ocean temperatures are projected to warm	• +1.0°C (RCP2.6) to +3.0°C (RCP8.5): top 100 m • +0.5°C (RCP2.6) to +1.5°C (RCP8.5): 1 km depth	(IPCC, 2013)

Note. Near term projections: 2016-2035. Long term projections: 2081-2100. Reference period: 1986-2005.

Talk about climate change refers most of the time to temperature change. Temperature is the first parameter used to allude to climate change, and it is the simplest. When we reflect on future climate change and we want to quantify its magnitude, it has become normal refer to global warming and temperature increase. But temperature variation is only one of climate change manifestations.

Anyway, it is evident that all land regions and oceans are very likely to warm during the 21st century. The WGI of IPCC collected lots of data from literature. All the projections allude to a specific reference period. The period we are referring to is the interval from 1986 to 2005.

The projections are relative to two different time spans: a near term from 2016 to 2035 and a long term from 2081 to 2100. The research group during its review came to these conclusions.

Near term projections of Global Mean Surface air Temperature (GMST)

Climate projections are subject to several sources of uncertainty. The extent of agreement between the CMIP5 projections provides rough guidance about the likelihood of a particular outcome. But it must be kept firmly in mind that the real world could fall outside of the range spanned by these particular models (see Figure 3.1).

- +0.47°C to +1.00°C, CMIP5 projections under RCP4.5
- +0.39°C to +0.87°C, CMIP5 projections under RCP4.5, ASK approach (weighting models according to some measure of their quality: only some centers participating in CMIP5 have the specific integration required by ASK simulations)

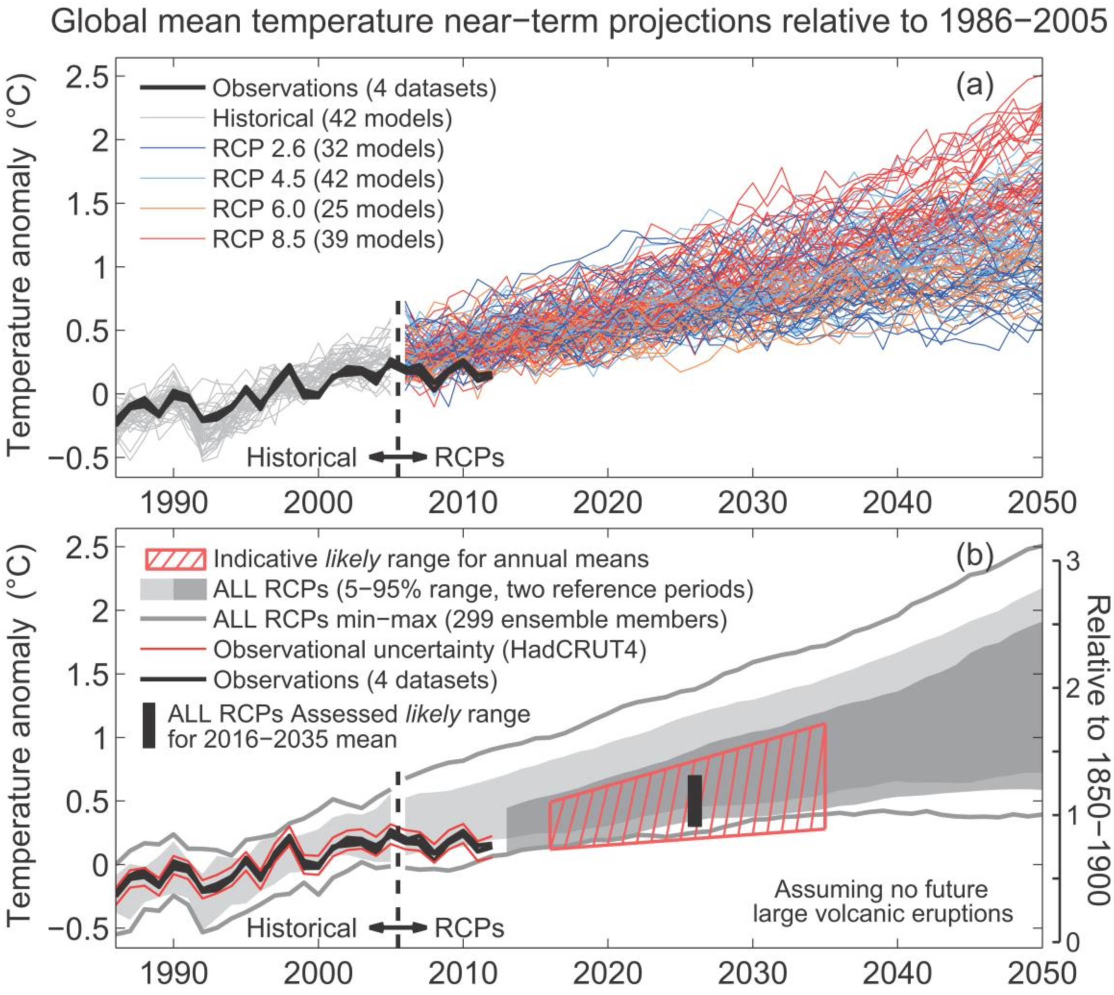

Figure 3.1 Synthesis of near-term projections of global mean surface air temperature (GMST). (a) Simulations and projections of annual GMST 1986-2050 (anomalies relative to 1986-2005). Projections under all RCPs from CMIP5 models. (b) As (a) but showing the 5 to 95% range of annual mean CMIP5 projections for all RCPs using a reference period of 1986-2005 (light grey shade) and all RCPs using a reference period of 2006-2012, together with the observed anomaly for (2006-2012) to (1986-2005) of 0.16°C (dark grey shade). (IPCC, 2013, p.1011)

Long term projections of Global Mean Surface air Temperature (GMST)

A consistent and robust feature across climate models is the continuance of global warming in the 21st century for all the RCP scenarios. Temperature increases are almost the same for all the RCP scenarios during the first two decades after 2005. At longer time scales, the warming rate begins to depend more on the specified GHG concentration pathway, being highest in RCP8.5 and significantly lower in RCP2.6, particularly afterwards 2050 when global surface temperature response stabilizes and declines thereafter (see Figure 3.2).

- +0.3°C to +1.7°C, CMIP5 under RCP2.6
- +1.1°C to +2.6°C, CMIP5 under RCP4.5
- +1.4°C to +3.1°C, CMIP5 under RCP6.0
- +2.6°C to +4.8°C, CMIP5 under RCP8.5

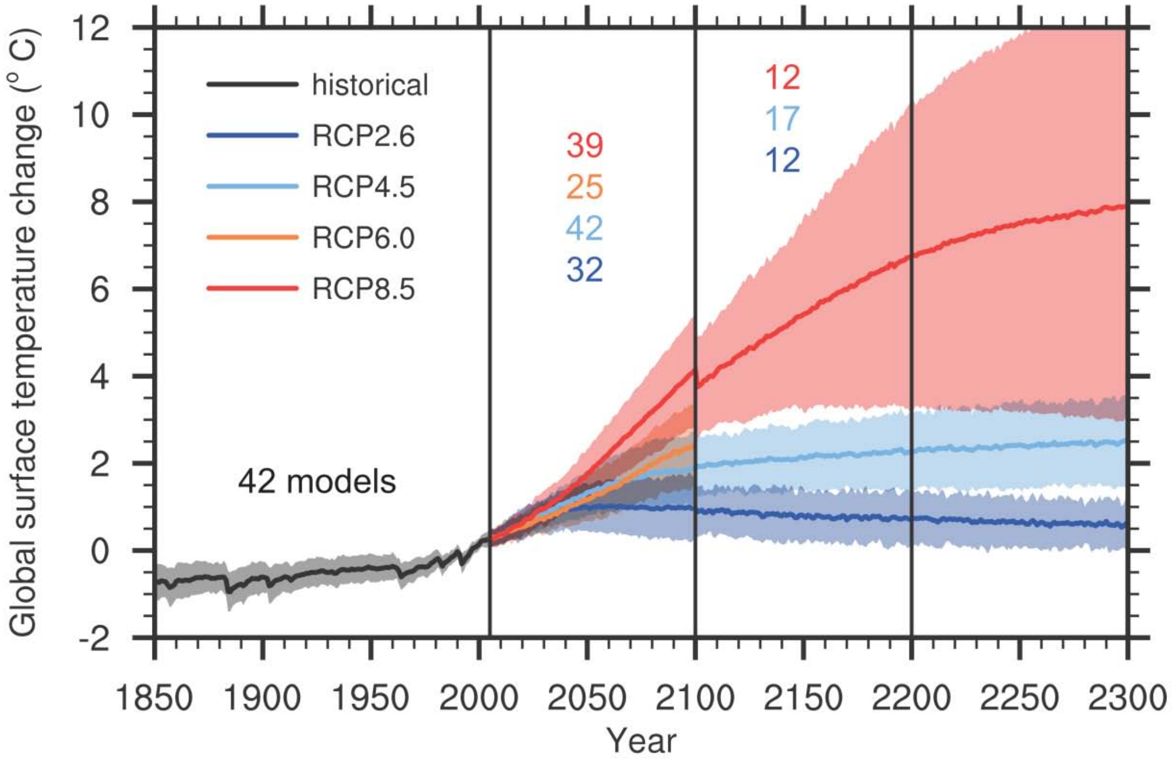

Figure 3.2 Time series of global annual mean surface air temperature anomalies (relative to 1986-2005) from CMIP5 concentration-driven experiments. Projections are shown for each RCP for the multi-model mean (solid lines) and ±1.64 standard deviation (5 to 95%) across the distribution of individual models (shading), based on annual means. (IPCC, 2013, p.89)

Figure 3.3 then shows the changes in annual mean temperatures in different time spans in the globe.

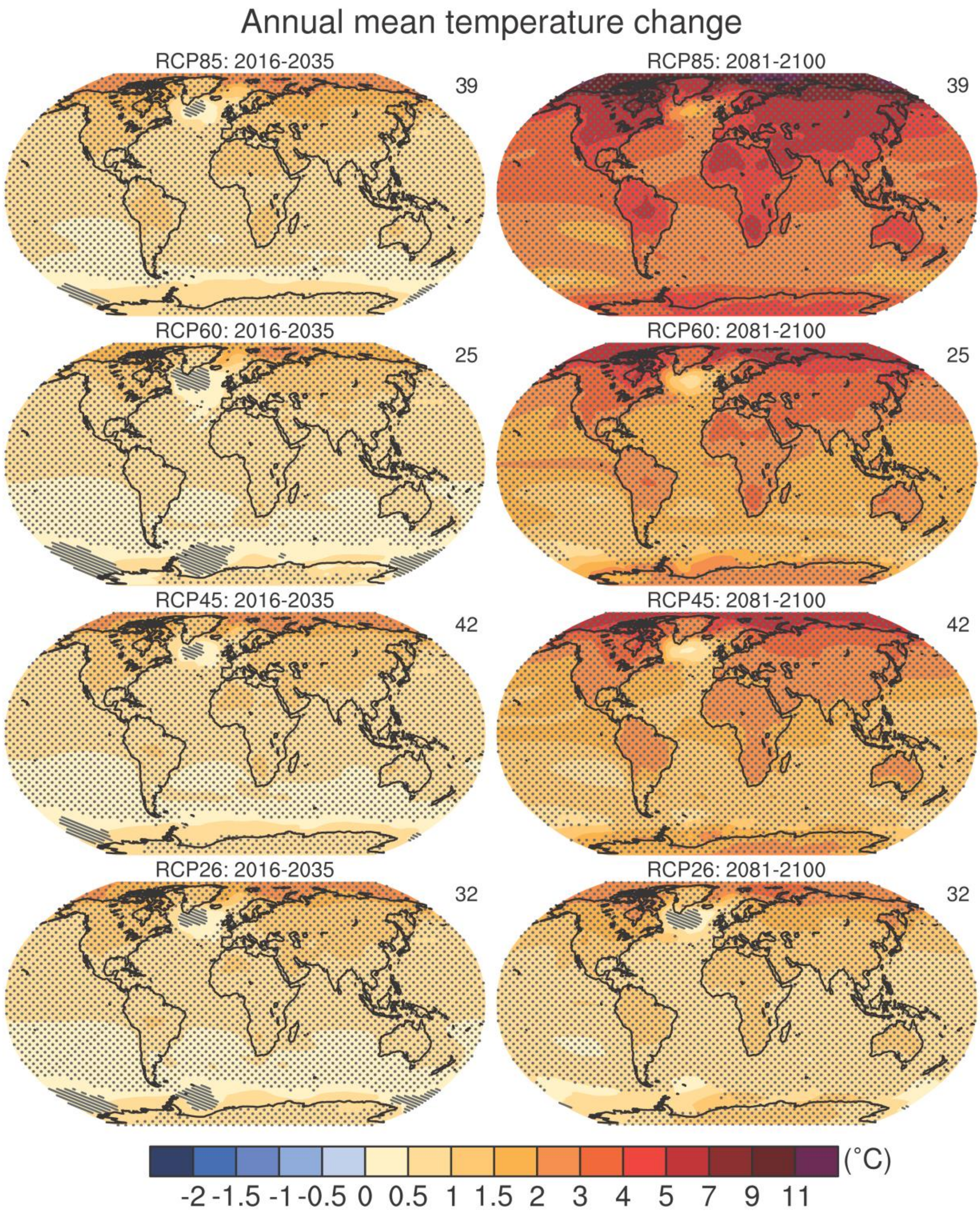

Figure 3.3 Multi-model ensemble average of annual mean surface air temperature change (compared to 1986–2005 base period) for 2016–2035 and 2081–2100, for RCP2.6, 4.5, 6.0 and 8.5. (IPCC, 2013, p.89)

Near term projection of ocean temperature

Globally averaged surface and near-surface ocean temperatures are projected to warm over the early 21st century, in response to both present day atmospheric concentrations of GHGs and projected future changes in RF (see Figure 3.4).

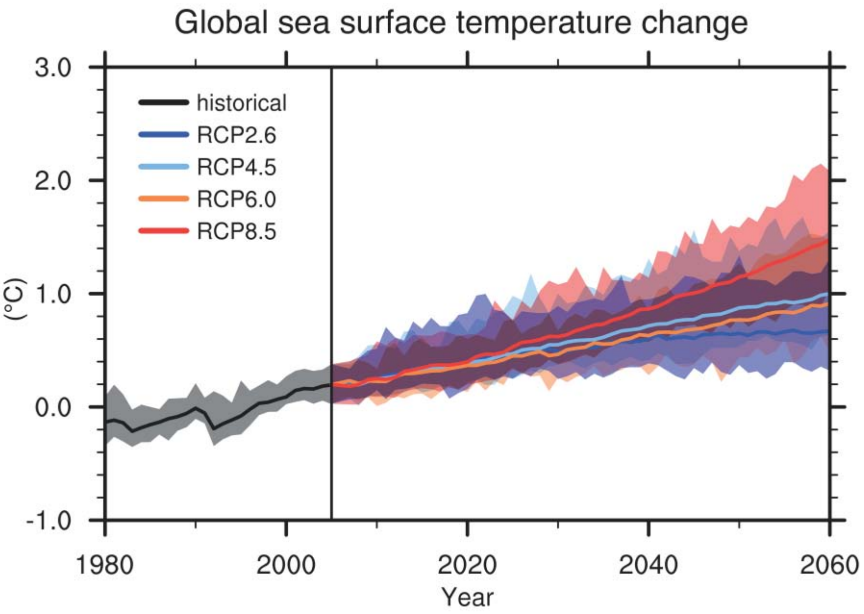

Figure 3.4 Projected changes in annual averaged, globally averaged, surface ocean temperature based on 12 Atmosphere-Ocean General Circulation Models (AOGCMs) from the CMIP5 multi-model ensemble, under 21st century scenarios RCP2.6, RCP4.5, RCP6.0 and RCP8.5. Shading indicates the 90% range of projected annual global mean surface temperature anomalies. (IPCC, 2013, p.993)

Globally averaged sea surface temperature shows substantial year-to-year and decade-to-decade variability, whereas the variability of depth-averaged ocean temperatures is much less. The rate at which globally averaged surface and depth-averaged temperatures rise in response to a given scenario for RF shows a considerable spread between models. In the CMIP5 models under all RCPs forcing scenarios, globally averaged sea surface temperatures are projected to be warmer over the near term relative to 1986–2005. Furthermore, as we can see in Figure 3.5, there are regional variations in the projected amplitude of ocean temperature change.

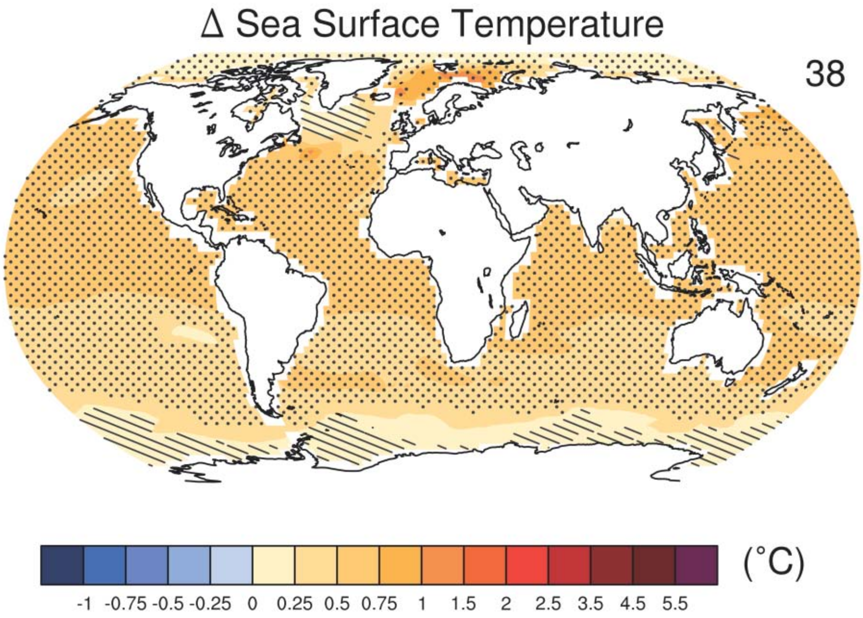

Figure 3.5 CMIP5 multi-model ensemble mean of projected changes in sea surface temperature for 2016–2035 relative to 1986–2005 under RCP4.5. The number of CMIP5 models used is indicated in the upper right corner. (IPCC, 2013, p.994)

Long term projection of ocean temperature

Projected increase of sea surface temperature and heat content over the next two decades is relatively insensitive to the emissions trajectory. However, projected outcomes diverge as the 21st century progresses. When sea surface temperatures increase as a result of external forcing, the interior water masses respond to the integrated signal at the surface, which is then propagated down to the greater depth.

Surface warming varies considerably between the emission scenarios, from about 1°C (RCP2.6) to more than 3°C in RCP8.5. Then depending on the emission scenario, global ocean warming between 0.5°C (RCP2.6) and 1.5°C (RCP8.5) will reach a depth of about 1 km by the end of the century. The strongest warming signal is found at the surface in subtropical and tropical regions.

3.1.2 Projected changes in precipitation

Table 3.3 Projected climate change's impacts on precipitation

IMPACT	NEAR TERM PROJECTIONS	LONG TERM PROJECTIONS	REFERENCE
PRECIPITATION PATTERN	-7% to +22% (CMIP5, RCP4.5)	• +0.5 to 4%/°C (CMIP5, RCP2.6) • +1 to 3%/°C (CMIP5, other RCPs)	(IPCC, 2013)

Note. Near term projections: 2016-2035. Long term projections: 2081-2100. Reference period: 1986-2005.

The second most obvious climate change manifestation is the change in precipitation pattern. Large-scale changes in precipitations are governed by processes, which are implemented in the RCP scenarios. These processes control the climatological distribution of precipitation and precipitation extremes. Precipitation is sustained by the availability of the moisture and energy. In a globally averaged sense the oceans provide an unlimited supply of moisture, therefore precipitation formation is energetically limited. Locally precipitation can be greatly modified by limitations in the availability of moisture (for instance over land) and the effect of circulation systems, although they are subject to local energetic constraints. Moisture and energy availability can be altered by climate change and in particular by global warming, the increase of radiative forcing caused by an increase in well-mixed GHG concentrations and the interactions between aerosol and clouds.

As for temperatures, the Working Group I collected data and supplied projections for two different periods, 2016-2035 and 2081-2100, related to the reference period 1986-2005.

Near term changes in precipitation (2016-2035)

The two graphs in Figure 3.6 show the CMIP5 multi-model projections of changes in annual and zonal mean precipitation (a) and annual and zonal precipitation minus evaporation [mm/day] (b) under RCP4.5. From these graphs we clearly understand that precipitation pattern will depend on the location of the region, because all regions have different peculiarities. Zonal mean precipitation will very likely increase in high and some of the middle latitudes and will increase just a bit in the subtropics. At more regional scales precipitation change may be influenced by anthropogenic aerosol emissions and will be strongly influenced by natural internal variability. From the diagram (a) of Figure 3.6 we can extract the range of changes in near term precipitation, which is -7% to +22%.

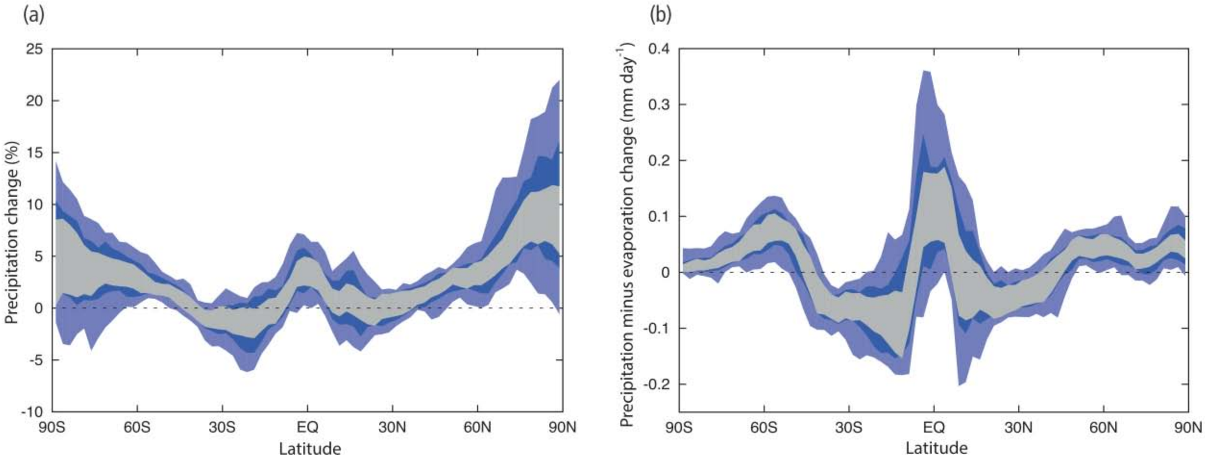

Figure 3.6 CMIP5 multi-model projections of changes in annual and zonal mean (a) precipitation (%) and (b) precipitation minus evaporation (mm day^{-1}) for the period 2016–2035 relative to 1986–2005 under RCP4.5. The light blue denotes the 5 to 95% range, the dark blue the 17 to 83% range of model spread. The grey indicates the 1σ range of natural variability derived from the pre-industrial control runs. (IPCC, 2013, p.985)

Long term changes in precipitation (2081-2100)

Long term precipitation changes are mainly driven by the increase of the surface temperature and other factors, as presented above. Projected precipitation changes vary greatly between models, more than temperature’s projections. The precipitation changes exhibit patterns that become more pronounced and definite as temperatures increase.

On planetary scale, relative humidity is projected to remain roughly constant, but specific humidity is projected to increase due to warming climate. For this reason, in the long term it is quite sure that global precipitation will grow with increased GMST (Global Mean Surface Temperature). Global mean precipitation will increase at a rate per °C smaller than of atmospheric water vapor. It will likely rise by 0.5 to 4%/°C for scenario RCP2.6 at the end of the 21st century. The range of sensitivities in the CMIP5 models for other scenarios is 1 to 3%/°C. Figure 3.7 shows the maps of multi-model results for the various RCPs scenarios in 2081-2100.

As we can appreciate in Figure 3.7, changes in average precipitation in a warmer world will exhibit substantial variation under RCP8.5. Some regions will experience increase, other regions will experience decreases and yet others will not experience significant changes at all.

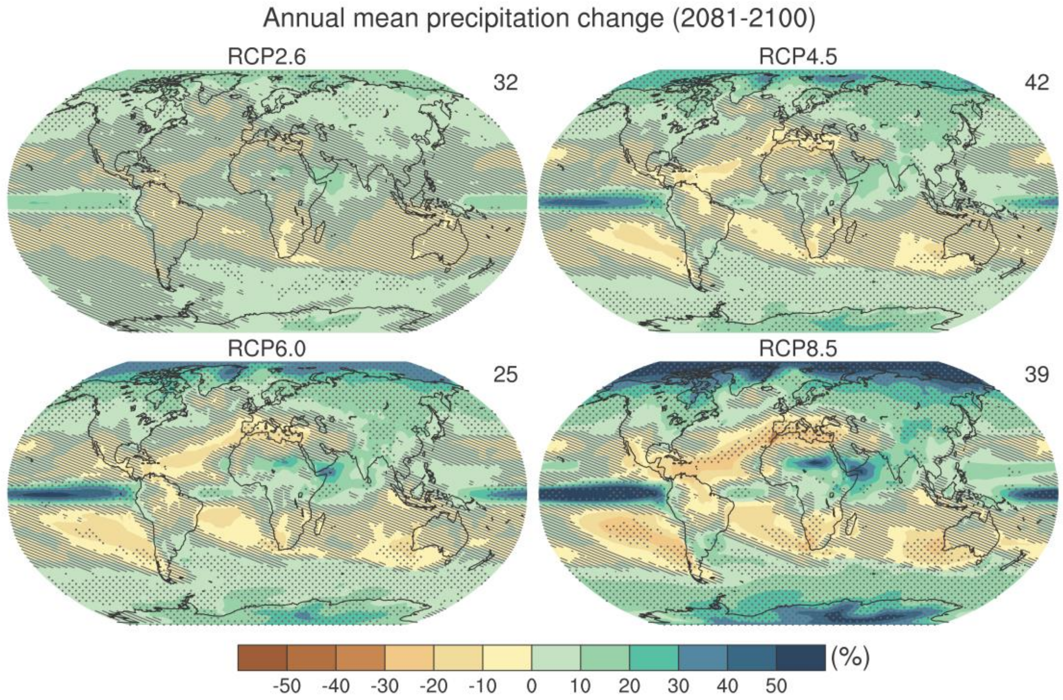

Figure 3.7 Maps of multi-model results for the scenarios RCP2.6, RCP4.5, RCP6.0 and RCP8.5 in 2081-2100 of average percent change in mean precipitation. Changes are shown relative to 1986–2005. The number of CMIP5 models to calculate the multi-model mean is indicated in the upper right corner of each panel. (IPCC, 2013, p.91)

The contrast of annual mean precipitation between dry and wet regions and the contrast between wet and dry seasons will increase over the most of the globe as temperatures increase. The general pattern of change indicates that high latitudes are very likely to experience greater amounts of precipitation. Many mid-latitude and subtropical arid and semi-arid regions will likely experience less precipitation and many moist mid latitude regions will likely experience more precipitation by the end of this century under the RCP8.5.

3.1.3 Projected changes in extreme events

Table 3.4 Projected climate change's impacts on precipitation

IMPACT	NEAR TERM PROJECTIONS	LONG TERM PROJECTIONS	REFERENCE
TEMPERATURE	Warm days • 20-26% (CMIP5, RCP2.6) • 20-28% (CMIP5, RCP6.5) • 20-30% (CMIP5, RCP8.5) Cold days • 4.0-6.0% (CMIP5, RCP2.6) • 3.5-6.0% (CMIP5, RCP6.5) • 3.0-6.0% (CMIP5, RCP8.5)	Warm days • 24-34% (CMIP5, RCP2.6) • 35-45% (CMIP5, RCP6.5) • 55-70% (CMIP5, RCP8.5) Cold days • 3.0-4.5% (CMIP5, RCP2.6) • 1.5-3.0% (CMIP5, RCP6.5) • 0.5-1.0% (CMIP5, RCP8.5)	(IPCC, 2013)
PRECIPITATION	Daily local extremes +5 to 10% per °C of warming	+5% (RCP2.6) to +20% (RCP8.5)	(IPCC, 2013)
ATMOSPHERIC CIRCULATION	Increase of North Atlantic hurricane intensity	Increase in the frequency of category 4-5 tropical cyclones in the North Atlantic and SW Pacific	(IPCC, 2013)
SEA LEVEL	Increase of sea level extremes	Increase of sea level extremes	(IPCC, 2013)

Note. Near term projections: 2016-2035. Long term projections: 2081-2100. Reference period: 1961-1990.

Several different atmospheric phenomena belong to the category of extreme events. As temperature and precipitation, they are not originated by climate change. The magnitude of the different kinds of extreme events is what is altered by climate change. As already mentioned, changes in many extreme weather and climate events have been observed since the middle of 20th century. These changes will be still present in the future and they will be even stronger.

As for temperature and precipitation, the Working Group I of the IPCC in their assessment *Climate change 2013: the physical science basis: Working Group I contribution to the Fifth assessment report of the Intergovernmental Panel on Climate Change* (IPCC, 2013) reported the data of projected changes they had sifted out from literature in two different time frames: in a near term (2016-2035) and in a long term (2081-2100) timeline. Air temperature, precipitation, atmospheric circulation and sea are the elements most affected by these changes.

Temperature

In the AR4 the extreme changes in temperature were analyzed focusing on two different measurements: warm days and nights and cold days and nights. Subsequent studies confirmed the conclusions of the AR4: cold episodes are projected to decrease significantly in a future warmer climate and heat waves would be more intense, more frequent and last longer towards the end of the 21st century. These trends were reported in the AR5 in a figure portrayed in Figure 3.8. The CMIP5 model ensemble exhibits a significant decrease in the frequency of cold nights, an increase in the frequency of warm days and nights and an increase in the duration of warm spells. For the next few decades, as we can see in the Figure, these changes are remarkably insensitive to the emission scenario considered. In most land regions and in the near term, the frequency of warm days and warm nights will thus continue to increase, while that of cold days and cold nights will continue to decrease.

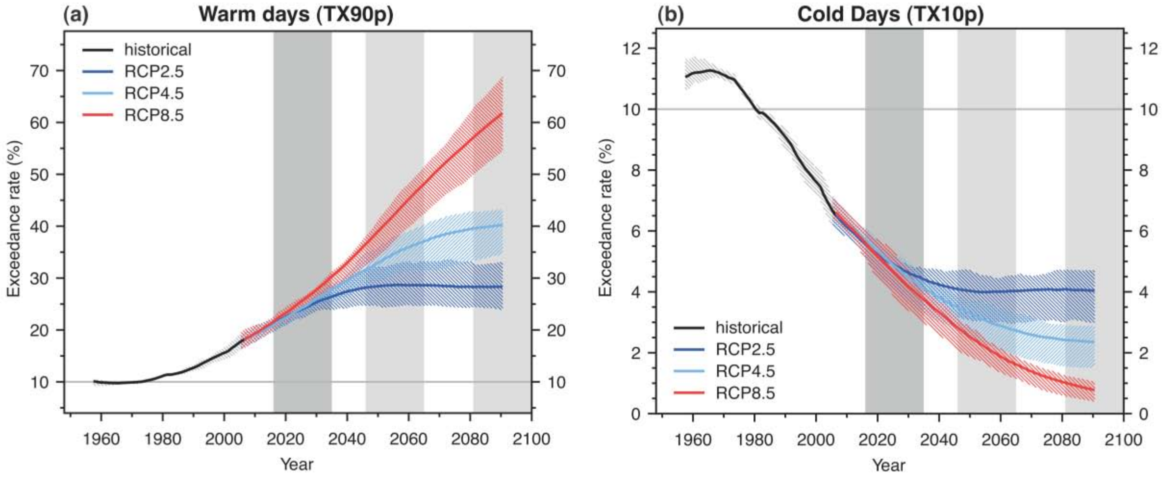

Figure 3.8 Global projections of the occurrence of (a) warm days (TX90p) and (b) cold days (TX10p). Results are shown from CMIP5 for the RCP2.6, RCP4.5 and RCP8.5 scenarios. Solid lines indicate the ensemble median and shading indicates the interquartile spread between individual projections (25th and 75th percentiles). (IPCC, 2013, p.990)

Anyway, from these diagrams we can extrapolate the future tendencies of warm days and cold days, which are reported in the summary table.

Prior to report a specific number we must describe the meaning of the measurements warm days and warm nights. Warm days are the percentage of annual days with daily T_{max} exceeding 90th percentile of T_{max} for 1961-1990. Cold days on the other hand are the percentage of annual days with T_{max} below 10th percentile of T_{max} for 1961-1990. Whit these definitions we can report future ranges of changes in warm days and cold days.

Near term projections of warm days
- 20-26% CMIP5 under RCP2.6
- 20-28% CMIP5 under RCP6.5
- 20-30% CMIP5 under RCP8.5

Near term projections of cold days
- 4.0-6.0% CMIP5 under RCP2.6
- 3.5-6.0% CMIP5 under RCP6.5
- 3.0-6.0% CMIP5 under RCP8.5

Long term projections of warm days
- 24-34% CMIP5 under RCP2.6
- 35-45% CMIP5 under RCP6.5
- 55-70% CMIP5 under RCP8.5

Long term projections of cold days
- 3.0-4.5% CMIP5 under RCP2.6
- 1.5-3.0% CMIP5 under RCP6.5
- 0.5-1.0% CMIP5 under RCP8.5

It is also very useful to communicate a detail of future long term projection of temperature changes. For high emissions scenarios, it is likely that in most land regions a current 1-in-20-year maximum temperature event will at least double in frequency, but in many regions will become an annual or a 1-in 2-year event.

Precipitation

For the 21st century the AR4 concluded that heavy precipitation events were likely to increase in many areas of the globe. Since AR4 larger number of additional studies have been published using global and regional climate models. For the near term, CMIP5 global confirm a clear tendency for increases in heavy precipitation events in the global mean, but there are significant variations across regions. Over most of the mid-latitude land masses and over wet tropical regions, extreme precipitation will be more intense and more frequent in a warmer world. Even if there has been substantial progress between CMIP3 and CMIP5 in the ability of models, to simulate more realistic precipitation extremes, the majority of models underestimate the sensitivity of extreme precipitation to temperature variability or trends, which implies that models may underestimate the projected increase in extreme precipitation in the future. Anyway, there is high confidence that changes in local extremes on daily and sub-daily time scales are expected to increase by roughly 5 to 10% per °C of warming.

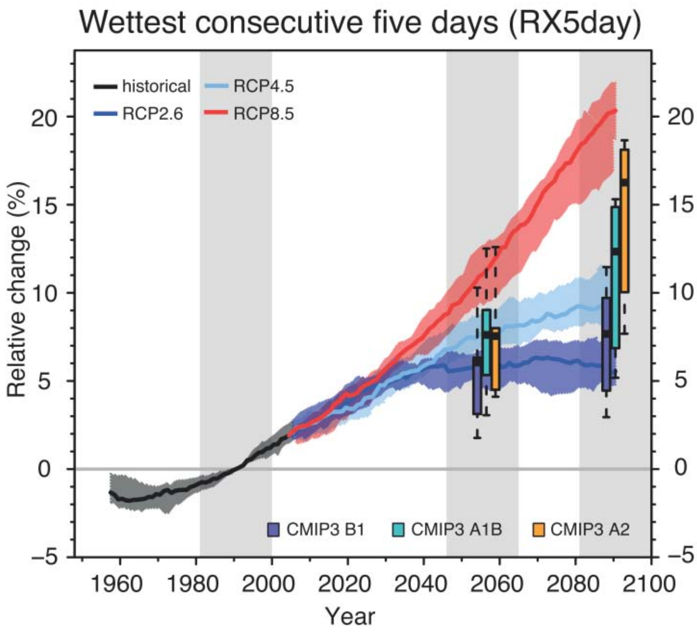

Figure 3.9 Global average percent change over land regions for the RCP2.6, RCP4.5 and RCP8.5 scenarios. (IPCC, 2013, p.1083)

The rate of increase air temperature is so important for the evaluation of precipitation because, for some scientists, extreme precipitation events occur when most of the available atmospheric water vapor rapidly precipitates out in a single storm. The maximum amount of water vapor in air (saturation) is determined by the Clausius-Clapeyron relationship. As air temperatures increases, this saturated amount of water also increases. If the amount of water vapor content in air is higher, the magnitude of the extreme event will be higher. Figure 3.9 shows projected 5-day precipitation over land regions obtained from the CMIP5 models. It is projected that during very wet 5-day periods at the end of 21st century, there will be a change into the range from 5% (RCP2.6) to 20% (RCP8.5) of more precipitation.

Atmospheric circulation

Variations in atmospheric circulation cause modifications in distinct large-scale climate phenomena that affect regional climate, as monsoons, cyclones, tropical cyclones, hurricanes and El Niño Southern Oscillation (ENSO). There are fewer studies that have explored changes in these kind of phenomena: thus there are few results and there is generally medium confidence on them.

Global measures of monsoon by the area will increase in the 21st century, while the monsoon circulation weakens. Monsoon onset dates are likely to become earlier or not to change much, while monsoon withdrawal dates are likely to delay, resulting in a lengthening of the monsoon season in many regions. The increase in seasonal mean precipitation is pronounced in the East and South Asian summer monsoons, while the change in other monsoon regions is subject to uncertainties. However, in South America, Africa, East Asia, South Asia, Southeast

Asia and Australia it is almost certain there will be a future increase in precipitation extremes related to monsoon.

Tropical rainfall changes are likely shaped by current climatology and ocean warming pattern. The first effect is to increase rainfall near the currently rainy regions, and the second effect increases rainfall where the ocean warming exceeds the tropical mean. The tropical Indian Ocean for example will feature a zonal pattern with reduced warming and decreased rainfall in the east and enhanced warming and increased rainfall in the west. However, there is low confidence in global projections of trends in tropical cyclone frequency in the 21st century, not only in the Indian Ocean but all over the world. Projections indicated that the global frequency of tropical cyclones will either decrease or remain essentially unchanged, concurrent with an increase in both global mean tropical cyclone maximum wind speed and rain rates.

As reported in the Fifth Assessment Report of IPCC (IPCC, 2013, p.992), hurricanes were explored by two studies, in which the authors measured different hurricane intensities. They projected near-term increases of North Atlantic hurricane intensity, driven in large part by projected reductions in North Atlantic tropospheric aerosols in CMIP5 future forcing scenarios. Studies projected near term increases in the frequency category 4-5 tropical cyclones in the North Atlantic and southwest Pacific, and also projected a mid-century intensification. However, several studies agree on the factors that lead to variations in tropical cyclones and hurricanes. Modes of climate variability that in the past have led to these variations in the intensity, frequency and structure of these climate phenomena – such as the ENSO – will continue influencing these extreme events through the mid-21st century.

El Niño Southern Oscillation (ENSO) will remain the dominant mode of natural climate variability in the 21st century, with global influences in the 21st century, and the regional rainfall variability it induces will intensify. Natural variations of the amplitude and spatial pattern of ENSO are so large that confidence in any projected change for the 21st century remains low. In a warmer climate, the increase in atmospheric moisture intensifies temporal variability of precipitation even if atmospheric circulation variability remains the same.

Sea level

The magnitude of extreme sea level events has increased since 1970 and most of this rise can be explained by increases in mean sea level. In the future it is very likely that there will be a significant increase in the occurrence of sea level extremes and, similarly to past observations, this increase will primarily be the result of an increase in mean sea level. These projections have been obtained studying several regional storm-surges in the southeastern coast of Australia, in the eastern Irish Sea, in the North Sea and in the United Kingdom coasts.

3.2 Expected climate change's impacts on energy system

This section is the most important part of the first third of the thesis, because in this section we display the future expected climate impacts on energy system. This is so important because it is the first step to find the vulnerabilities of the system and then an appropriate solution.
As we have already asserted, we consider the energy sector divided into three main aspects: energy resource, energy demand and energy supply. Then we minutely examine apart water, because it is firmly linked and strongly affects many portions of the energy structure, even if we estimate it as part of a specific sector of energy entity, the resource one.
Similarly to the accounting of impacts on the elements of energy system, we illustrate the various predicted data and ranges of change in an effect-and-cause pattern: it is provided a backward account of the distinct elements which affect each unit of the electric energy system.

3.2.1 Expected impacts on water

Water, judged as an energy resource, might be altered by numerous factors, which we could concentrate into three main elements, that are summed up in Figure 2.1. These elements specifically are climate change, temperature and precipitation, and they have affected and will affect several traits of the water resource, as the level of the sea or water availability for energy production.
A specific description of all the traits of water resource is drawn up in the following passages.

3.2.1.1 Climate change's impacts on water

Table 3.5 Projected climate change's impacts on water resource

IMPACT	NEAR TERM PROJECTIONS	LONG TERM PROJECTIONS	REFERENCE
SEA ICE EXTENT	Nearly ice-free Arctic Ocean in September (sea ice extent less than 1×10^6 km^{2}for at least 5 consecutive years) before 2050 for RCP8.5	NH reduction in mean sea ice extent • 8% for RCP2.6 to 34% for RCP8.5 in February • 43% for RCP2.6 to 94% for RCP8.5 in September NH reduction in mean sea ice volume • 29% for RCP2.6 to 73% for RCP8.5 in February • 54% for RCP2.6 to 96% for RCP8.5 in September SH reduction in mean sea ice extent • 16% for RCP2.6 to 67% for RCP8.5 in February • 8% for RCP2.6 to 30% for RCP8.5 in September SH reduction in mean sea ice volume • Nearly ice-free state for RCP8.5 in February • 60% under RCP4.5 in February	(IPCC, 2013)

IMPACT	NEAR TERM PROJECTIONS	LONG TERM PROJECTIONS	REFERENCE
SNOW COVER EXTENT	NH SCE for a March to April average • -5.2%±1.9% under RCP2.6 • -5.3%±1.5% under RCP4.5 • -4.5%±1.2% under RCP6.0 • -6.0%±2.0% under RCP8.5	NH SCE for a March to April average • -7%±4% under RCP2.6 • -13%±4% under RCP4.5 • -15%±5% under RCP6.0 • -25%±8% under RCP8.5	(IPCC, 2013)
PERMAFROST	Annual mean near-surface area • -21% ± 5% under RCP2.6 • -18% ± 6% under RCP4.5 • -18% ± 3% under RCP6.0 • -20% ± 5% under RCP8.5	Annual mean near-surface area • -37% ± 11% under RCP2.6 • -51% ± 13% under RCP4.5 • -58% ± 13% under RCP6.0 • -81% ± 12% under RCP8.5	(IPCC, 2013)
EVAPORATION	Generally +1 to 3% for each degree of increase Increases over most of the oceans Increases or decreases over land following precipitation pattern over land		(IPCC, 2013)

Note. Near term projections: 2016-2035. Long term projections: 2081-2100. Reference period: 1986-2005.

As for temperature, precipitation and extreme events, investigative scientists have conducted different projections in different time scales of future impacts of climate change into water system. The Working Group I of the IPCC in the *Fifth Assessment Report* (IPCC, 2013) organized all data and ranges in literature into two main categories: near term projections, which consider especially as projections' period the years from 2016 to 2035, and long term projections, which on the other hand consider as projections' period the years from 2081 to 2100.

Climate change influences numerous elements, which are part of the water system. We could include into two main categories, the cryosphere and the evaporation.

Cryosphere

Cryosphere is the collective term for the components of the Earth system, that contain a substantial fraction of water in the frozen state. It comprises several components, which are sensitive to changes in air temperature and precipitation and hence to climate change in general. Specifically, researchers have realized projections on three specific components of the cryosphere, which are sea ice, snow cover and permafrost.

- *Sea ice extent*

  Sea ice extent is one of the most familiar and most sensible data of climate change for population, because it is a simple and visible confirmation of global warming. There is lots of literature which treats this argument in a very detailed way. Scientists for example carried out specific projections on sea ice extent of the Northern Hemisphere (NH) and of the Southern Hemisphere (SH) and specific projections for winter months and summer months, considering February and September as reference months.

  Changes in external forcing affect interannual and decadal variability of climate and this complicates the ability to make specific, precise short-term projections of changes in the cryosphere. Data in our possession are principally related to long term, but also near term projections are well considered.

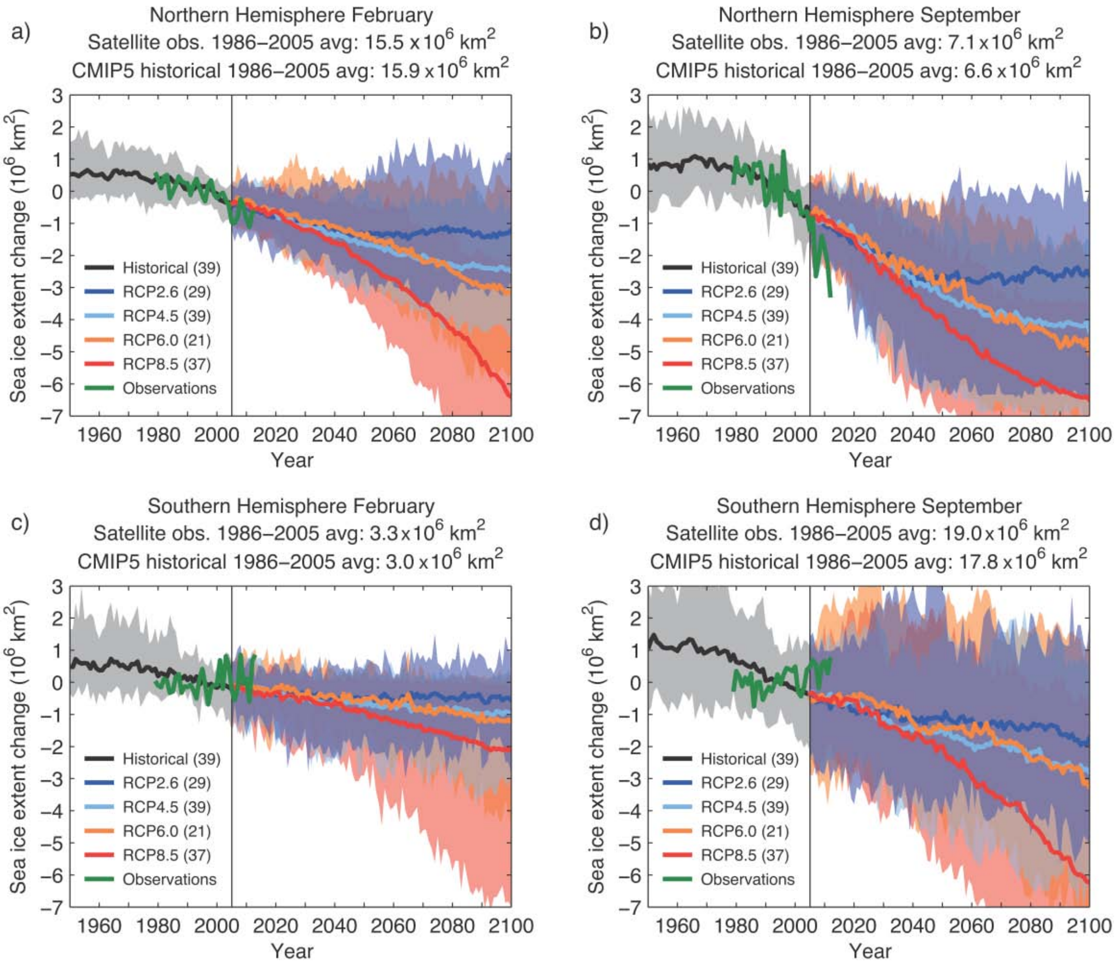

Figure 3.10 Changes in sea ice extent as simulated by CMIP5 models over the second half of the 20th century and the whole 21st century under RCP2.6, RCP4.5, RCP6.0 and RCP8.5 for (a) Northern Hemisphere February, (b) Northern Hemisphere September, (c) Southern Hemisphere February and (d) Southern Hemisphere September. Changes are relative to the reference period 1986–2005. The solid curves show the multi-model means and the shading denotes the 5 to 95% range of the ensemble. (IPCC, 2013, p.1088)

Most of the CMIP5 models project a nearly ice-free Arctic at the end of summer by 2100 in the RCP8.5 scenario (nearly ice-free Arctic: sea ice extent less than 1 x 10^6 km^2 for at least 5 consecutive years). Some other models of the CMIP5 instead show large changes in the near term. Previous models project an ice-free summer period in the Arctic Ocean by 2040. By scaling six CMIP3 models to recent observed September sea ice changes, a nearly ice-free Arctic in September is projected to occur by 2037, reaching the first quartile of the distribution for timing of September sea ice loss by 2028. However, a number of models that have fairly thick Arctic sea ice, produce a slower near-term decrease in sea ice extent compared to observations. An accurate analysis of CMIP3 model simulations found out that, for near-term predictions, the dominant factor for decreasing sea ice is increased ice melt and reductions in ice growth play a secondary role. This reason may explain the underestimation in CMIP3 projections.

Regarding the end of the 21st century, based on the analysis of CMIP3 climate change simulations, the AR4 concludes that the Arctic and Antarctic sea ice covers are projected to shrink under all SRES scenarios (the emission scenarios used by the IPCC in its Third and Fourth Assessment). It also stresses that, in some projections, the Arctic Ocean becomes almost entirely ice-free in late summer during the second half of the 21st century. These conclusions were confirmed by further analyses of the CMIP3 archives and were strengthened by the CMIP5.

Experts made projections for the period 2081-2100 on the mean sea ice areal coverage and the mean sea ice volume of the NH and SH in February and September related to the time period 1986-2005. The results, shown in Figure 3.10, are:

NH reduction in mean sea ice extent
- 8% for RCP2.6 to 34% for RCP8.5 in February
- 43% for RCP2.6 to 94% for RCP8.5 in September

NH reduction in mean sea ice volume
- 29% for RCP2.6 to 73% for RCP8.5 in February
- 54% for RCP2.6 to 96% for RCP8.5 in September

SH reduction in mean sea ice extent
- 16% for RCP2.6 to 67% for RCP8.5 in February
- 8% for RCP2.6 to 30% for RCP8.5 in September

SH reduction in mean sea ice volume
- Nearly ice-free state for RCP8.5 in February
- 60% under RCP4.5 in February

As we can notice from the data, CMIP5 models reach nearly ice-free conditions during September in the Arctic before 2100 under RCP8.5 (see Figure 3.11). The percentages in February of sea ice volume are higher than the corresponding ones for sea ice extent, which is indicative of a substantial sea ice thinning. Arctic sea ice cover will continue to shrink and thin all year round during the 21st century as the annual mean global surface temperature rises.

- *Snow cover extent*

  We define snow cover extent (SCE) as the snow that covers ice-free land areas, and not all the snow on global surface. Analyses of seasonal snow cover changes generally focus on the NH, where the configuration of the continents on the Earth induces a larger maximum seasonal SCE and a larger sensitivity of SCE to climate changes. Decreases of SCE are strongly connected to a shortening of seasonal snow cover duration and are related to both precipitation and temperature changes, thus to climate change in general.

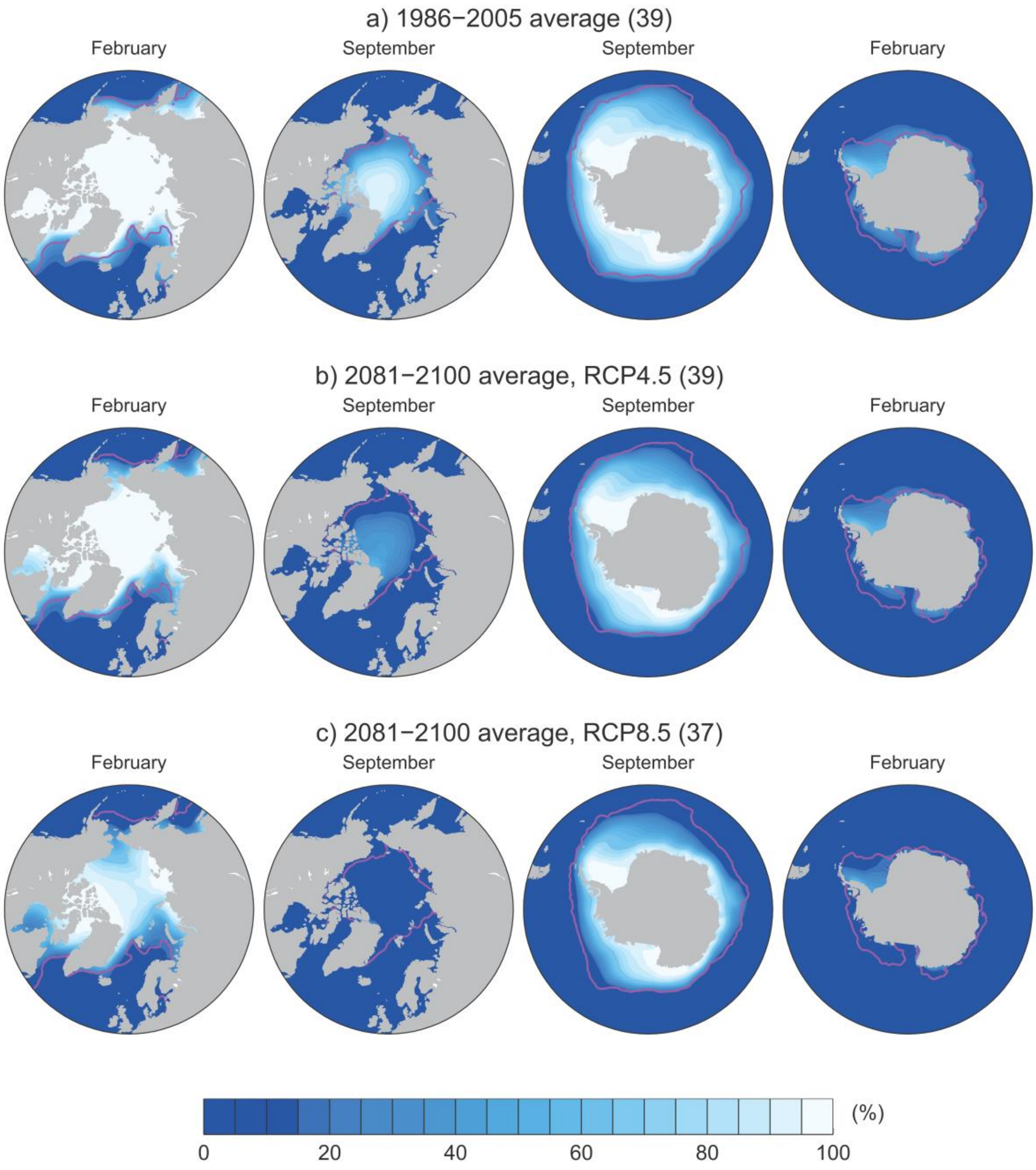

Figure 3.11 February and September CMIP5 multi-model mean sea ice concentration (%) in the Northern and Southern Hemispheres for the periods (a) 1986–2005, (b) 2081–2100 under RCP4.5 and (c) 2081–2100 under RCP8.5. (IPCC, 2013, p.1089)

For example, projected increases in snowfall across much of the northern high latitudes act to increase snow amounts, but warming reduces the fraction of precipitation that falls as snow.

Figure 3.12 shows the Northern Hemisphere spring (March to April average) snow cover extent change (in %) in the CMIP5 ensemble, relative to the simulated extent for the 1986-2005 reference period. And the projections, in the near and long term, could be recapped in this way:

NH SCE for a March to April average for period 2016-2035:

- -5.2%±1.9% under RCP2.6
- -5.3%±1.5% under RCP4.5
- -4.5%±1.2% under RCP6.0
- -6.0%±2.0% under RCP8.5

NH SCE for a March to April average for period 2081-2100:

- -7%±4% under RCP2.6
- -13%±4% under RCP4.5
- -15%±5% under RCP6.0
- -25%±8% under RCP8.5

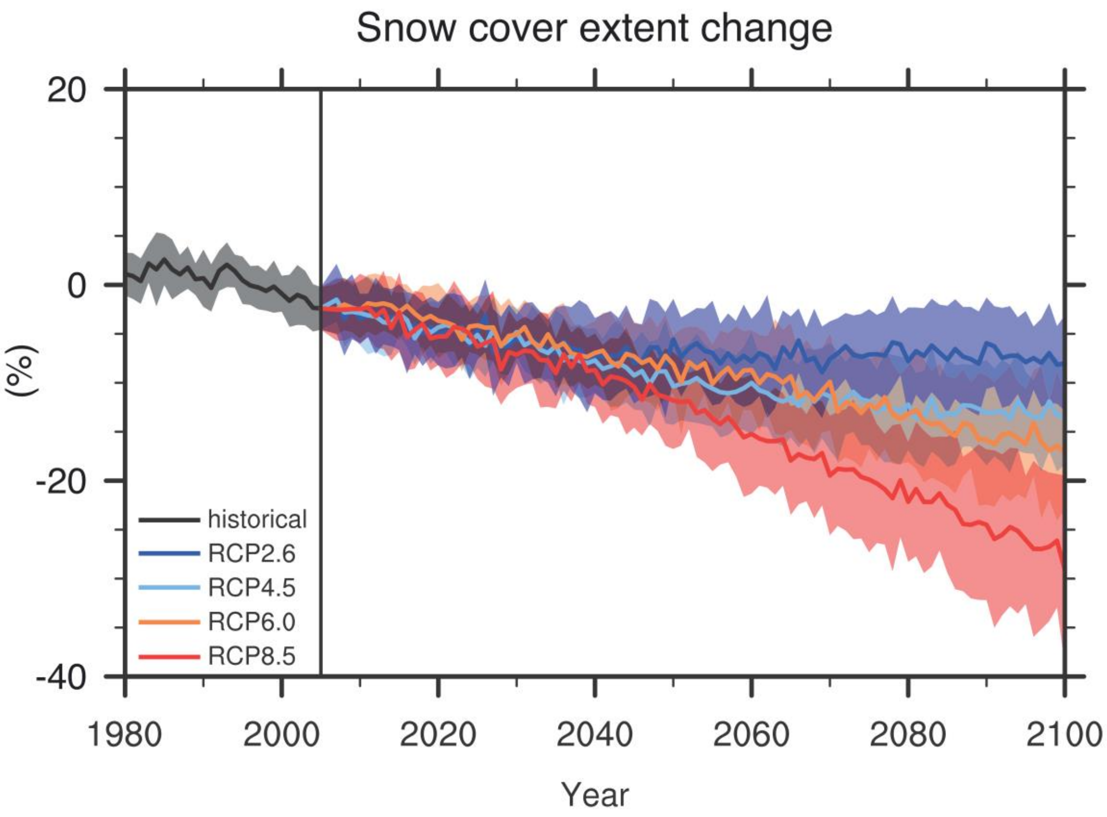

Figure 3.12 Northern Hemisphere spring (March to April average) snow cover extent change (in %) in the CMIP5 ensemble, relative to the simulated extent for the 1986–2005 reference period. Thick lines mark the multi-model average, shading indicates the inter-model spread (one standard deviation). (IPCC, 2013, p.1092)

- *Permafrost*

  The strong projected warming across the northern high latitudes in climate model simulations has implications for frozen ground. Recent projections of the extent of near-surface permafrost degradation continue to vary widely depending on the underlying climate forcing scenario and model physics, but virtually all of them indicate substantial near-surface permafrost degradation and thaw depth deepening over much of the permafrost area. Permafrost at greater depths is less directly relevant to the surface energy and water balance, and its degradation naturally occurs much more slowly. Climate models are beginning to represent permafrost physical processes and properties more accurately, thus the projections have increased credibility compared to the previous generation of models assessed in the AR4. The projected changes in permafrost are a response not only to warming but also to changes in snow conditions, because snow properties and their seasonal evolution exert significant control on soil thermal state.

All near term projections indicate a substantial amount of near-surface permafrost degradation (typically taking place in the upper 2 to 3 m) and thaw depth deepening over much of the permafrost area. The same trend was determined for long term projections. The ranges, which are related to the reference period 1986-2005, are shown in Figure 3.13 and are reported below:

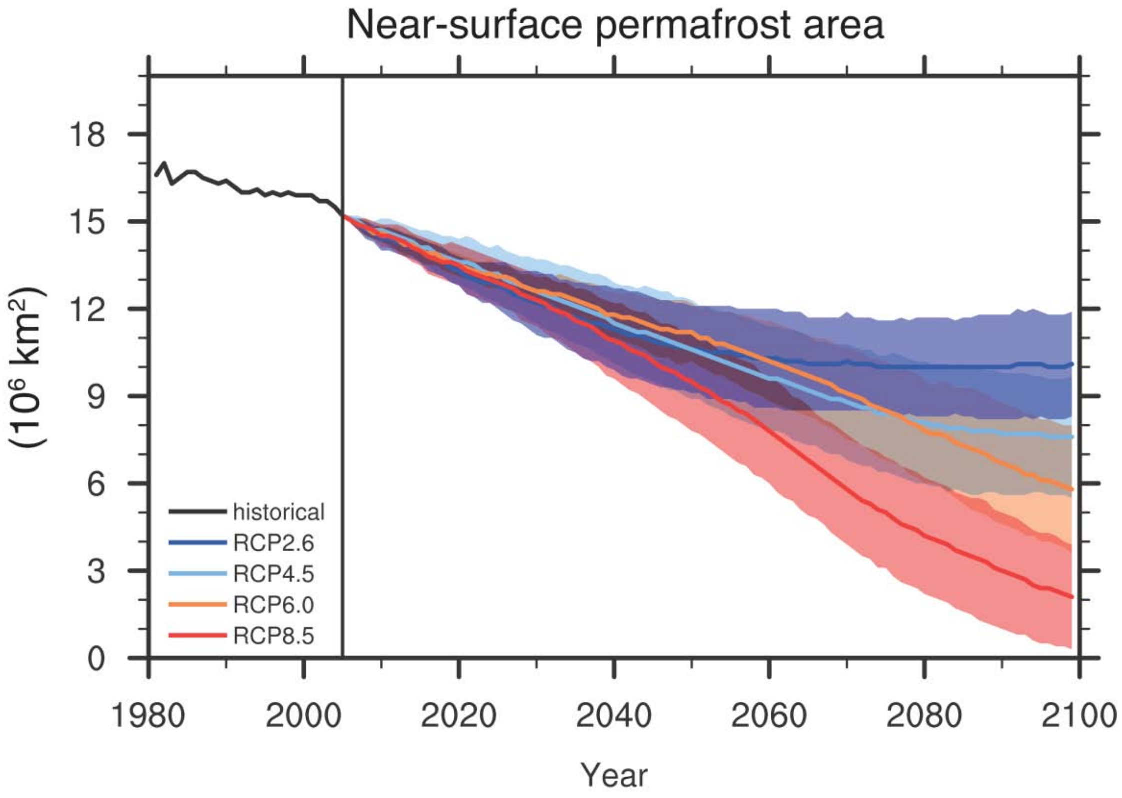

Figure 3.13 Northern Hemisphere near-surface permafrost area, diagnosed for the available CMIP5 models using 20-year average bias-corrected monthly surface air temperatures and snow depths. Thick lines: multi-model average. Shading and thin lines indicate the inter-model spread (one standard deviation). (IPCC, 2013, p.1092)

o Annual mean near-surface permafrost area for period 2016-2035:	-21% ± 5% under RCP2.6 -18% ± 6% under RCP4.5 -18% ± 3% under RCP6.0 -20% ± 5% under RCP8.5
o Annual mean near-surface permafrost area for period 2080-2099:	-37% ± 11% under RCP2.6 -51% ± 13% under RCP4.5 -58% ± 13% under RCP6.0 -81% ± 12% under RCP8.5

Evaporation

Anthropogenic forcing provokes an increase in precipitation in some areas of the world. The variability of the atmospheric moisture storage is negligible, thus to balance the increase in precipitation (which requires a certain amount of water) it is necessary a global mean increase in evaporation. Global atmospheric water content is constrained by the Clausius-Clapeyron equation to increase at around 7%/K; however both evaporation and precipitation in global warming simulations increase at 1 to 3%/K (IPCC, 2013, p.986).

Annual mean surface evaporation in the models assessed in AR4 showed increase over most of the ocean and increases or decreases over land, with largely the same pattern over land as increases and decreases in precipitation. Similar behavior occurs in ensemble of CMIP5 models. Evaporation increases over most of the ocean and land, with prominent areas of decrease over land occurring in southern Africa and northwest Africa along the Mediterranean. The areas of decrease correspond to areas with reduced precipitation. In fact, if we take a look to Figure 3.14 which exhibits the annual mean evaporation change at the end of the 21st century, and we compare it with Figure 3.7 which presents the annual mean precipitation change for the same period, we can observe that changes in precipitation and evaporation go hand in hand: where there is an increase of precipitation there is a similar increment also for evaporation.

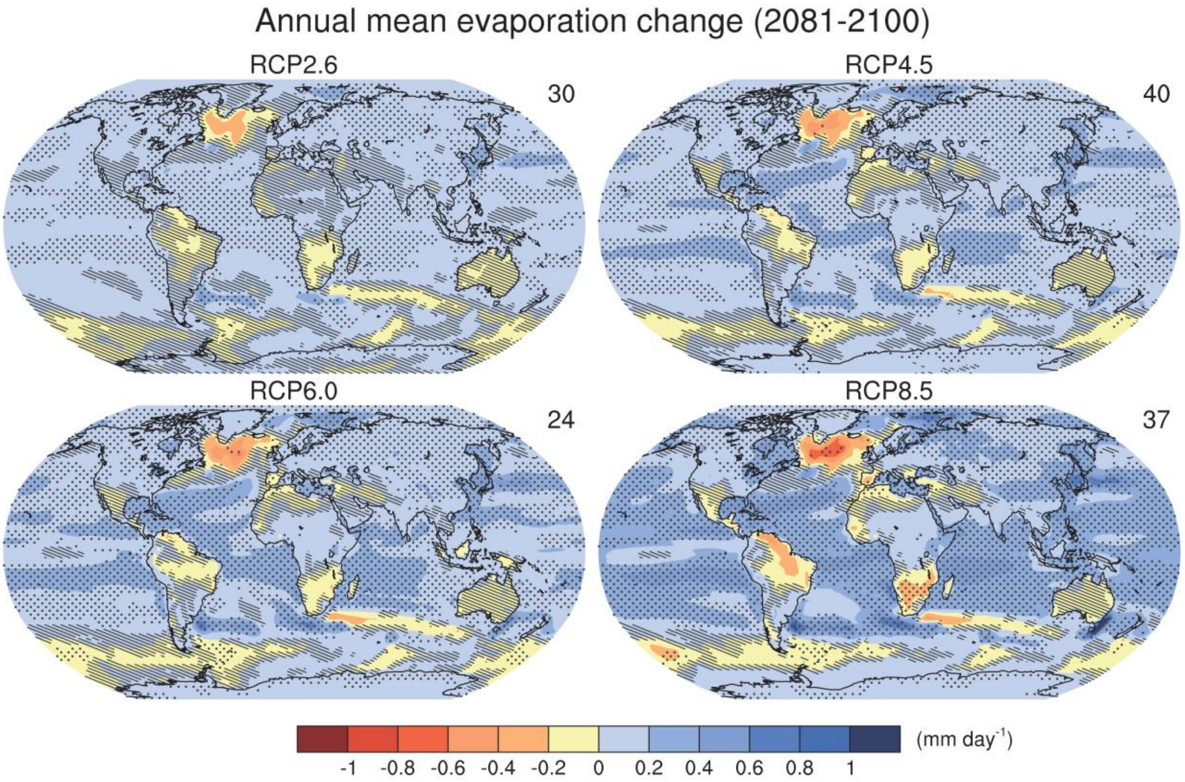

Figure 3.14 Change in annual mean evaporation relative to the reference period 1986-2005 projected for 2081–2100 from the CMIP5 ensemble. The number of CMIP5 models used is indicated in the upper right corner of each panel. (IPCC, 2013, p.1082)

Figure 3.15 shows the CMIP5 multi-model annual mean projected changes for the period 2016-2035 relative to 1986-2005 under RCP 4.5 for the evaporation.

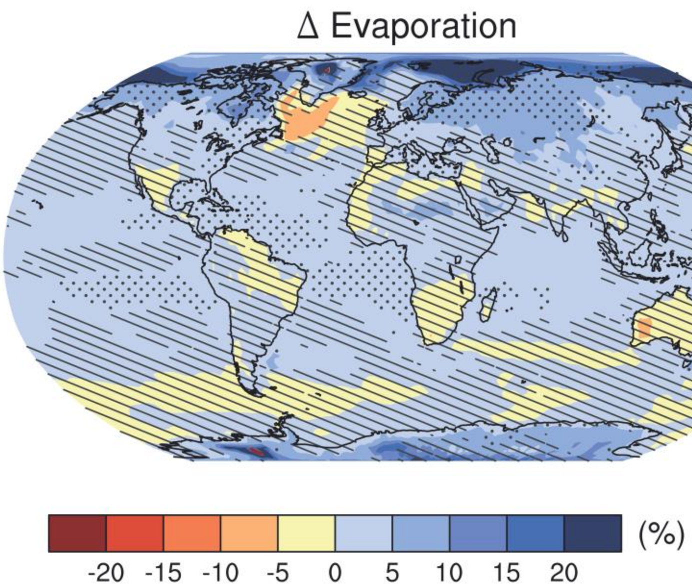

Figure 3.15 CMIP5 multi-model annual mean projected changes for evaporation (%) for the period 2016–2035 relative to 1986–2005 under RCP4.5 The number of CMIP5 models used is indicated in the upper right corner of the panel. (IPCC, 2013, p.987)

3.2.1.2 Impacts of temperature changes on water

Table 3.6 Projected impacts of temperature changes on water

IMPACT	PROJECTIONS	REFERENCE
GLOBAL	Median values and likely ranges for projections of global mean sea level (GMSL) rise • 0.40 [0.26 to 0.55]m (RCP2.6) • 0.47 [0.32 to 0.63]m (RCP4.5) • 0.48 [0.33 to 0.63]m (RCP6.0) • 0.63 [0.45 to 0.82]m (RCP8.5) Median values and likely ranges at 2100 • 0.44 [0.28 to 0.61]m (RCP2.6) • 0.53 [0.36 to 0.71]m (RCP4.5) • 0.55 [0.38 to 0.73]m (RCP6.0) • 0.74 [0.52 to 0.98]m (RCP8.5)	(IPCC, 2013)
HEAT EXPANSION	30 to 55% of the global projections • 0.14 [0.10 to 0.18]m (RCP2.6) • 0.19 [0.14 to 0.23]m (RCP4.5) • 0.19 [0.15 to 0.24]m (RCP6.0) • 0.27 [0.21 to 0.33]m (RCP8.5)	(IPCC, 2013)
GLACIER MELTING	15 to 35% of the global projections • 0.10 [0.04 to 0.16]m (RCP2.6) • 0.12 [0.06 to 0.19]m (RCP4.5) • 0.12 [0.06 to 0.19]m (RCP6.0) • 0.16 [0.09 to 0.23]m (RCP8.5)	(IPCC, 2013)

Note. Projections' period: 2081-2100. Reference period: 1986-2005.

Most of the Earth surface is covered by oceans and seas. Climate change as a whole affects the water sector and consequently the characteristics of oceans. But specifically global warming, which we could measure with the increase of temperatures, is altering and will continue to vary the level of seas and oceans.

Even in this case, all data and ranges of sea level rise summarized in Table 3.6 were collected by the Working Group I of the Intergovernmental Panel on Climate Change (IPCC) and were reported into the Fifth Assessment Report (AR5) *Climate change 2013: the physical science basis: Working Group I contribution to the Fifth assessment report of the Intergovernmental Panel on Climate Change* (IPCC, 2013).

The process-based projections for Global Mean Sea Level rise during the 21st century are the sum of contributions derived from models, which were evaluated by authors comparing them. The projections of GMSL rise for each RCP scenario are based on results from CMIP5 Atmosphere-Ocean General Circulation Models (AOGCMs provide a representation of the climate system that is near or at the most comprehensive end of the spectrum currently available: they are complex models). Researchers studied the contributors to global mean sea level rise, stating that thermal expansion and glacier melting have been the dominant contributors in the 20th century and that will be also in the future. But there are other contributors, which are: the Greenland ice-sheet surface mass balance change, Greenland ice-sheet rapid dynamical change, Antarctic ice-sheet surface mass balance change, Antarctic ice-sheet rapid dynamical change and anthropogenic intervention in water storage on land.

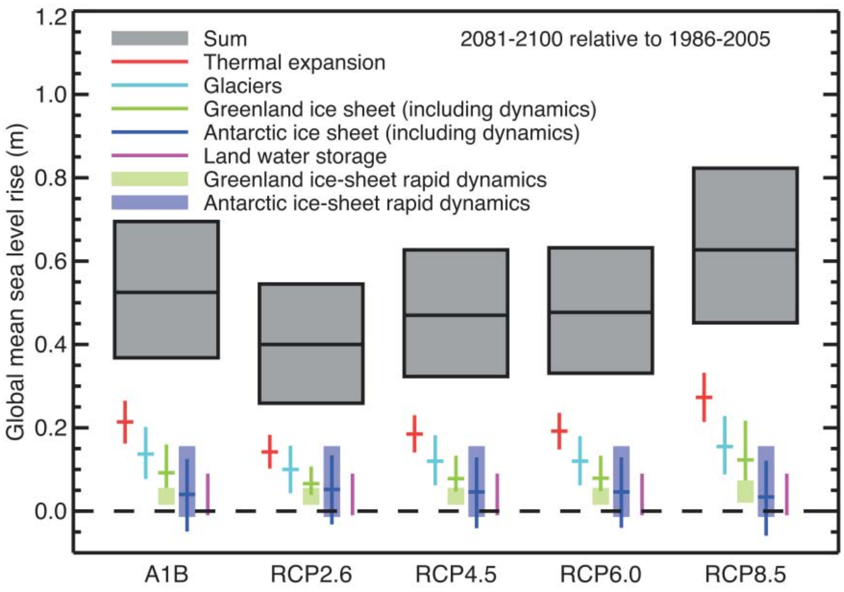

Figure 3.16 Projections from process-based models with likely ranges and median values for global mean sea level rise and its contributions in 2081–2100 relative to 1986–2005 for the four RCP scenarios and scenario SRES A1B used in the AR4. (IPCC, 2013, p.1180)

In this description we report the sum of the projected contributions and then only the ranges about the two major's contributors of sea level rise, as we can see in Table 3.6. This is due to the fact that thermal expansion and glacier contribution might account the 90% of future projections. However, Figure 3.16 show projections from process-based models, with likely ranges and median values for global mean sea level rise and its contributions in 2081-2100 relative to 1986-2005 for the four RCP scenarios ad scenario SRES A1B used in AR4.

By the late 21st century, in the period 2081-2100 relative to 1986-2005, the median values and likely ranges for projections of GMSL rise are:

- 0.40 [0.26 to 0.55]m under RCP2.6
- 0.47 [0.32 to 0.63]m under RCP4.5
- 0.48 [0.33 to 0.63]m under RCP6.0
- 0.63 [0.45 to 0.82]m under RCP8.5

Looking at these ranges and at Figure 3.16 we can notice that RCP4.5 and RCP6.0 are very similar at the end of the century: the difference is that RCP4.5 has a greater rate of rise earlier in the century than RCP6.0, which we can perceive in Figure 3.17. In Figure 3.17 we can also notice that the rate of rise becomes roughly constant before the middle of the century in RCP2.6, while in RCP4.5 and RCP6.0 becomes constant at the end of the century. Whereas in RCP8.5 acceleration of the rate continues throughout the century.

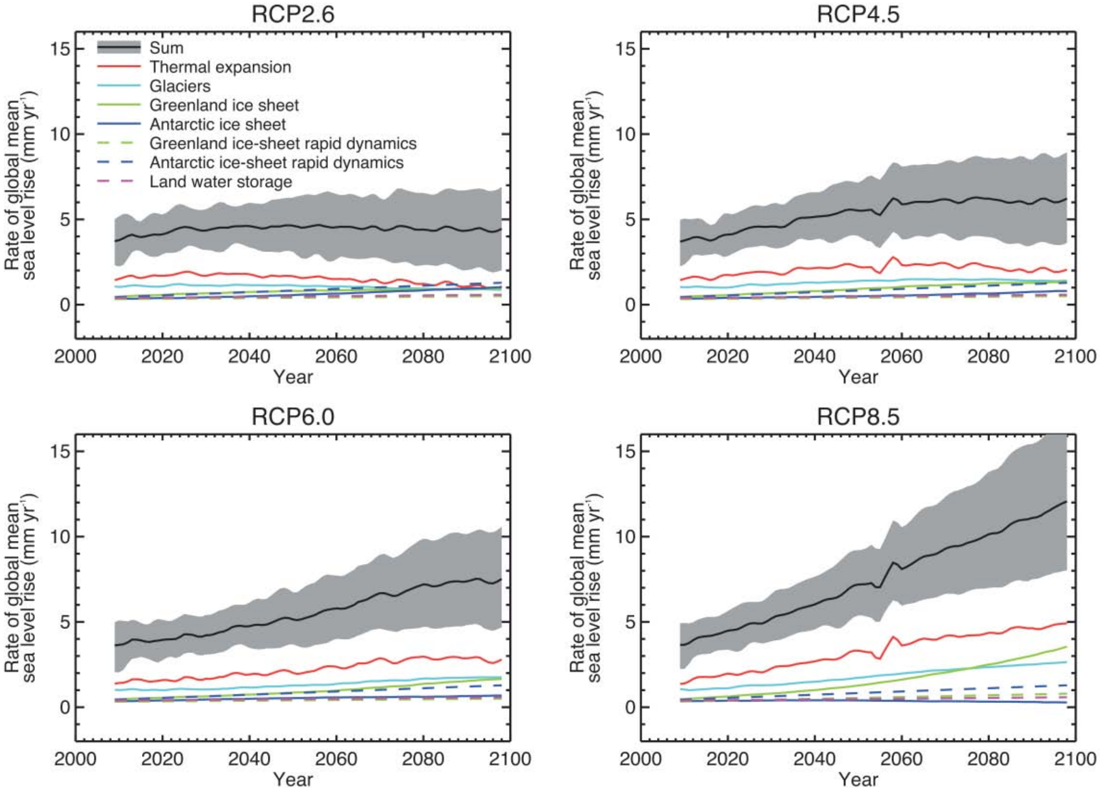

Figure 3.17 Projections from process-based models of the rate of GMSL rise and its contributions as a function of time for the four RCP scenarios and scenario SRES A1B. The lines show the median projections. (IPCC, 2013, p.1181)

At 2100 the median values and likely ranges for projections of GMSL rise are:

- 0.44 [0.28 to 0.61]m under RCP2.6
- 0.53 [0.36 to 0.71]m under RCP4.5
- 0.55 [0.38 to 0.73]m under RCP6.0
- 0.74 [0.52 to 0.98]m under RCP8.5

These values and likely ranges are drawn in Figure 3.18.

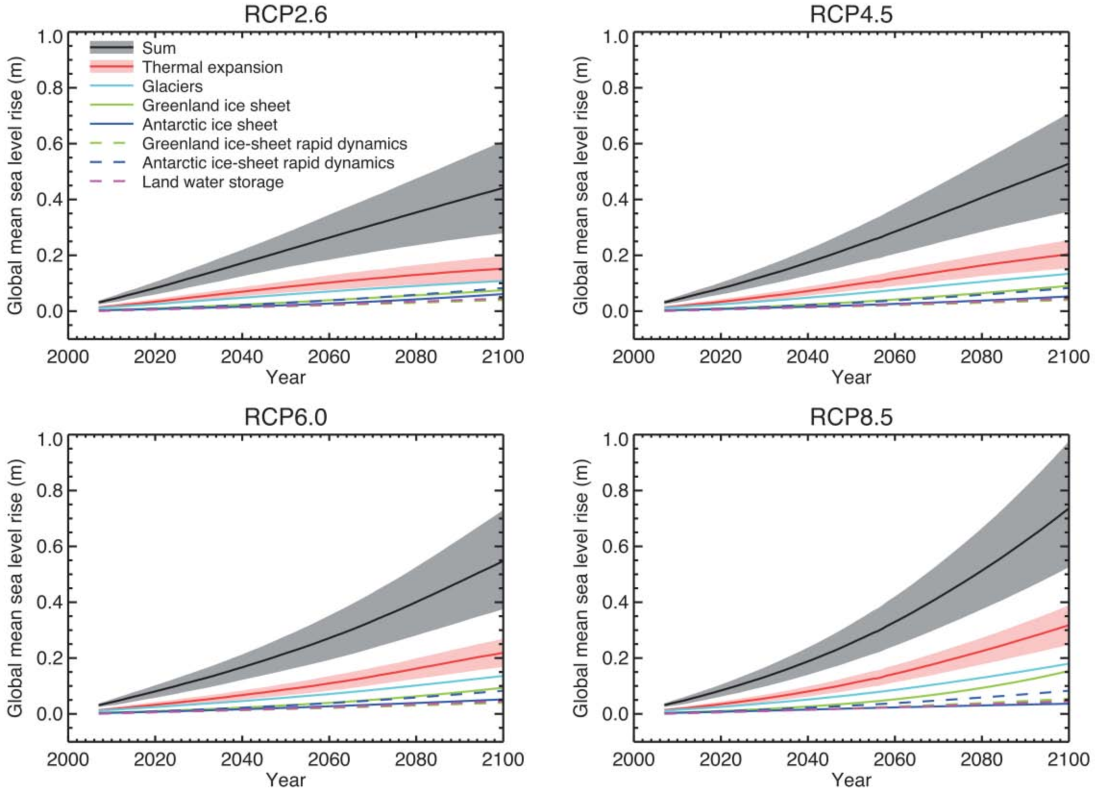

Figure 3.18 Projections from process-based models of global mean sea level (GMSL) rise relative to 1986–2005 as a function of time for the four RCP scenarios and scenario SRES A1B. The lines show the median projections. (IPCC, 2013, p.1181)

Figures 3.17 and 3.18 show not only the projections of the rate of Global Mean Sea Level rise and of GMSL rise relative to 1986-2005, but also its contributions. As already stated, the two major contributors are thermal expansion and glacier melting, whose contributions are:

Heat expansion (30 to 55% of the projections):
- 0.14 [0.10 to 0.18]m under RCP2.6
- 0.19 [0.14 to 0.23]m under RCP4.5
- 0.19 [0.15 to 0.24]m under RCP6.0
- 0.27 [0.21 to 0.33]m under RCP8.5

Glacier melting (15 to 35% of the projections):
- 0.10 [0.04 to 0.16]m under RCP2.6
- 0.12 [0.06 to 0.19]m under RCP4.5
- 0.12 [0.06 to 0.19]m under RCP6.0
- 0.16 [0.09 to 0.23]m under RCP8.5

The projections of thermal expansion do not include an adjustment of volcanic forcing in AOGCMs, as this is uncertainty and relatively small. Glacier melting excludes glaciers of

Greenland and Antarctica, but includes glaciers peripheral to the Greenland ice-sheet. By 2100, 15 to 55% of the present volume of glaciers outside Antarctica is projected to be eliminated under RCP2.6, and 35 to 85% under RCP8.5.

3.2.1.3 Impacts of precipitation changes on water

Table 3.7 Projected impacts of precipitation's changes on water

IMPACT	PROJECTIONS	REFERENCE
FLOODS	No general global trend. Northern high latitudes: upward trend. Europa and Asia: upward, downward or no trend.	(IPCC, 2013)
DROUGHTS	Low confidence on the magnitude of future impacts. Increases of meteorological droughts in the Mediterranean, Central America, Brazil, south Africa and Australia. Decreases in high northern latitudes.	(IPCC, 2013)
STREAMFLOWS	General trend: decline in spring and summer streamflows and an increase in streamflows in winter	(California Climate Change Center, 2006)
SALINITY	Sea Surface Salinity. Subtropical regions and Atlantic more saline. High latitudes and North Pacific less saline.	(IPCC, 2013)

As already widely discussed, the several consequences of climate change into the natural system, as a whole, are affecting and will increasingly impact the systems that constitute the energy system, as the water system. But we could associate some specific repercussions on water system with the changes of precipitation patterns. These effects are floods, droughts, changes in streamflows and salinity.

Flooding principally occurs from heavy rainfall, but especially when natural watercourses do not have the capacity to convey excess water. Thus the causes could be associated to a natural event but also to system incapacity. For these reasons it is difficult to find a general global trend of floods, as the Working Group II of the IPCC concluded in the AR4. However, in the AR5 WGII assesses floods in regional detail, justifying this stance with the fact that trends in floods are strongly influenced by changes in river management. The most evident flood trends appear to be in northern high latitudes, where observed warming trends have been largest. Studies for Europe and Asia show evidence for upward, downward or no trend in the magnitude and frequency of floods, so that there is currently no clear and widespread evidence for observed changes in flooding except for the earlier spring flow in snow-dominated regions. In summary, there continues to be a lack of evidence on flood projections and thus low confidence regarding the sign of trend in the magnitude and frequency on a global scale.

Drought condition may occur for many reasons, but the main is the change of precipitation pattern. If a reduction of precipitation takes place, it is very likely that a meteorological drought occurs. Dry periods, in any case, could result from other changes in the precipitation pattern, associated with additional agents. Increased temperatures for example will lead to more precipitation falling as rain rather than snow, earlier snowmelt and increased evaporation and transpiration. Low precipitation and timing of water availability (associated with high temperatures but also with changes in soil moisture) can cause agricultural droughts. The risk of future agricultural droughts episodes will increase in the regions of robust soil moisture decrease (IPCC, 2013, p.1086). However, there is low confidence in the magnitude of future impacts (agriculture and meteorological droughts), even though substantial increases of meteorological drought are projected in the Mediterranean, Central America, Brazil, South Africa and Australia, while decreases are projected in high northern latitudes.

Floods and droughts are not the only effects of the change of the rainfall pattern. The same motivations, which can lead to agricultural droughts, will probably affect the hydrology of several basins around the world. The California Climate Change Center in its report *Climate change impacts on high-elevation hydropower generation in California's Sierra Nevada: a case study in the upper American river* (California Climate Change Center, 2006) studied the problems of hydropower generation connected with water availability. They run simulations for two locations under two different models for two greenhouse gas scenarios (A2 and B1 which belong to the SRES scenarios and not to the RCPs), yielding a total of eight perturbation ratios. They carried out streamflow predictions for 2070-2099 compared with an unimpaired natural streamflow representing the period 1960-1990. The results are displayed in Figures 3.19 and 3.20.

The general trend that can be appreciated from these projections is a decline in spring and summer streamflows and an increase in streamflows in winter. This translates into an earlier timing of inflows. Each month was divided into equalized sets of wet, normal and dry days. Averages were taken of all wet, normal and dry January days, and so on, generating three series of monthly perturbation ratios. The results show that, in general, daily maximum streamflows increase more than medium and low streamflows (wet, normal and dry days). The percentage changes to annual streamflow for the whole system for all scenario, referred to the historical scenario, are:

- 71% for PCMB1_38
- 86% for PCMB1_39
- 62% for GFDLA2_38
- 86% for GFDLA2_39

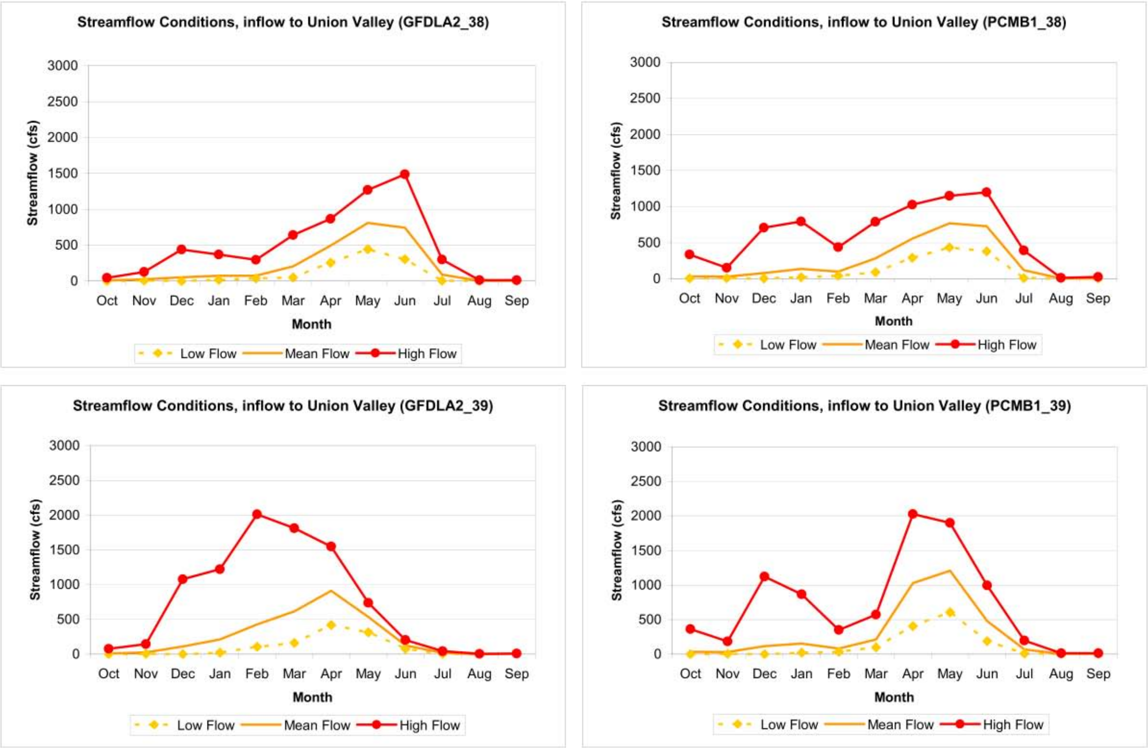

Figure 3.19 Streamflow conditions (unimpaired inflow to Union Valley) under climate change scenarios 2070-2099. Note: cfs = monthly natural flow cubic feet per second. 1 acre foot = 43.560 cubic feet = 1233.48 m^3. (California Climate Change Center, 2006, p.15)

Figure 3.20 Streamflow conditions (unimpaired inflow to Ice House) under climate change scenarios 2070-2099. (California Climate Change Center, 2006, p.16)

The modification of precipitation pattern has also had a huge influence on the salinity of water elements, as oceans, watercourses and lakes. Regions with high salinity where evaporation dominates precipitation have become more saline since the 50s and regions of low salinity where precipitation dominates have become fresher.

The Casamance estuary is a perfect example of the problem associated with this impact. In the report *Salinity in the Casamance estuary. Occurrence and consequences* (Blesgraaf et al., 2006) the authors reported the reasons for which the Casamance estuary had become hypersaline and the principal one is the decrease of precipitations. They studied if there is the possibility to return to the original conditions, refreshing the estuary or, in other words, flushing it. They found that the most important parameter that influences the flushing of the estuary is the rainfall, since this is a dominant parameter with a large variance. More rainfall will result in more runoff. However, from the model output they could conclude that the estuary reacts quick on a change in rain and runoff intensity, but several years of heavy rain is not enough to flush the estuary completely, which results in a hypersaline estuary in the dry season.

The WGI of IPCC in the AR5 communicated some long-term projections of global sea surface salinity (SSS). The CMIP5 climate model projections available suggest that high SSS subtropical regions that are dominated by net evaporation are typically getting more saline. Lower SSS regions at high latitudes are typically getting fresher. They also suggest a continuation of this trend in the Atlantic where subtropical surface water become more saline as the century progresses. At the same time the North Pacific is projected to become less saline. Figure 29 shows the projected sea surface salinity differences for 208-2100 for RCP8.5 relative to 1986-2005 from CMIP5 models.

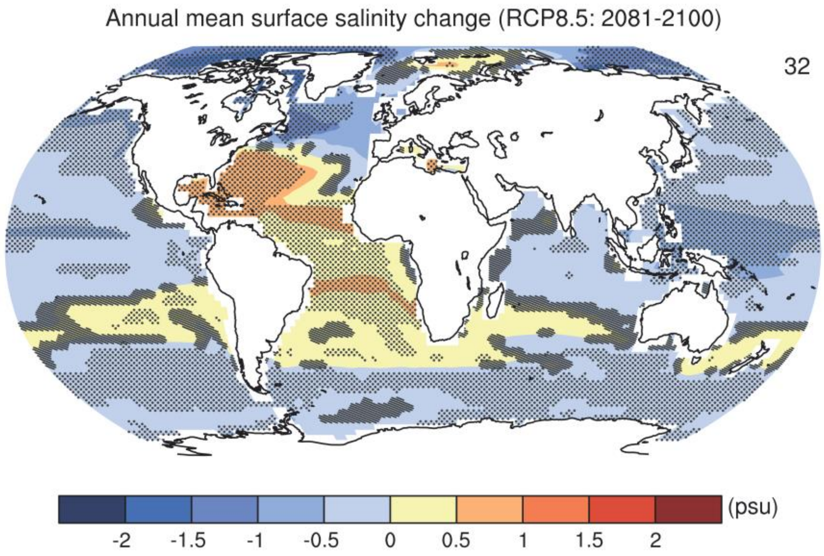

Figure 3.21 Projected sea surface salinity differences 2081-2100 for RCP8.5 relative to 1986-2005 from CMIP5 models. The number of CMIP5 models used is indicated in the upper right corner. Ocean salinity is generally defined as the salt concentration (e.g., Sodium and Chlorine) in sea water. It is measured in unit of PSU (Practical Salinity Unit), which is a unit based on the properties of sea water conductivity. 1 PSU = 1 g/kg. (IPCC, 2013, p.1094)

3.2.2 Expected impacts on energy resources

All those sources that may be used to generate electricity or other kinds of energy are considered energy resources. These sources fall into two categories: renewable and non-renewable resources. Wind, solar radiation, water, crops, oil, natural gas and coal are the sources we take in consideration in the investigation because they are all affected by climate change. In this section the focus is aimed at the energy endowment, to be more precise at the amount of primary energy available for every resource.

As previously explained when we introduced the impacts on energy resources in Chapter 2, we aggregate the climatic consequences, which affect the energy endowment under a unique parameter: the climate change. An exception is done for hydropower endowment, which we consider affected by only the water system in our analysis, for highlighting the strong correlation between the water system and the energy system.

3.2.2.1 Climate change's impacts on energy resources

Table 3.8 Projected climate change's impacts on energy resources

IMPACT	PROJECTIONS	REFERENCE
WIND	"Winners" and "losers": regions where wind energy may benefit and regions where wind energy may be negatively impacted	(Pryor and Barthelmie, 2010)
	Reference period: 1964 - 2000 Northwest U.S. Wind speeds. Summertime: -5-10% (wind power resource: -40%). Wintertime: possible slightly increase	(Sailor et al., 2008)
	Reference period: 1948 - 1978 Continental U.S. Wind speeds. -1.0 to -3.2% in the next 50 years. -1.4 to -4.5% over the next 100 years	(Breslow and Sailor, 2002)
	Reference period: 1980 - 2000 Baltic sea region. Wind power potential: +15% Ireland. Wind power potential. Wintertime: +4-8%. Summertime: decrease UK. Wind speeds. Summertime: -5% (-15% in Northern Ireland). Wintertime: increases Eastern Mediterranean. Wind speeds. Increases over land and decreases over sea. Noticeable increase over the Aegean sea	(Mideksa and Kallbekken, 2010)
BIOENERGY	Brazil. Projections: 2005-2030. Reference period: 1980-2000 Sugarcane. Planted area: +148%. Crop yield: +7% (from 77 to 82t/ha). Output: +161% Biodiesel. Shift of suitable growing zones for oilseed crops, from northeast to the south	(de Lucena et al., 2009b)
WAVE AND TIDAL	Relationship wind – wave energy +20% in mean wind speed raises mean wave heights around 44%, and raises available power levels by 133% -20% in mean wind speed lowers available power levels by 67%	(Harrison and Wallace, 2005)
FOSSIL FUELS	The access will be affected by climate change Coal. Precipitation increase: coal quality decrease, coal availability increase (no seam fires)	(Williamson et al., 2009)

This part treats the expected impacts of climate change and its consequences to all energy resources, except for hydropower one. The resources we consider in this section are wind, bioenergy, wave, tidal, oil, natural gas and coal. The endowment of these will be altered in different way. This is due to fact that these sources belong to different typologies of energy, renewable and non-renewable. The amount of energy of a renewable resource is closely related to climate parameters: thus the endowment of these resources varies with changes of climate variables. On the other hand, the amount of energy of a non-renewable resource does not vary with weather and climate change: it is the access to them that could be influenced by changes in climate, and thus varies the final endowment of the non-renewable resource.

Wind

The availability and reliability of wind power depend on weather conditions. Wind mills and wind farms must be placed in those sites where the statistics of wind (maximum, minimum, mean and variance) are optimal for energy production. Only few sites have the appropriate characteristics for this purpose and climate change and its consequences may introduce the risk of reduce wind power generation diminishing the endowment of wind. It may also occur the opposite situation: an inappropriate area could become suitable owing to climate change. Researches consequently investigate future wind patterns not only on those regions that are now suitable for wind power generation, but also on all other regions, which could become good enough. They do not concentrate only on the statistics of wind (mean wind speed and gustiness), but also on other factors which influence the wind resource. They concentrate on air density for example, because it is fundamental in giving the value of energy density of wind.

As for other energy resources, it does not exist a study where we can find comprehensive projections of wind pattern changes of all the world. This is due to fact that there was not so many research over this theme, but above all because it is quite difficult to elaborate global projections of wind changes. In literature we can find lots of precise studies which deal with specific regions or nations. Gathering together these studies permits to have a wider idea of global future changes in wind patterns and have an overview on how the studies are conducted: it could also permit to understand the general wind tendencies over the world. For example, we can deduce that wind statistics will change in different ways across regions, suggesting that it is necessary an accurate study for a specific region if we want to know in details future changes of wind pattern.
Hereinafter there is an account of some investigation over the endowment of wind resource.

Pryor and Barthelmie in *Climate change impacts on wind energy: a* review (Pryor and Barthelmie, 2010) mentioned some trends of wind energy density in the north and southeast of Europe, north and south America. They asserted that global climate change may change the geographic distribution and the inter-and intra-annual variability of the wind resource, or alter other aspects of the external conditions for wind developments. As in other components of climate change there will be "winners" and "losers": regions where wind energy developments may benefit from climate change and regions where the wind energy industry may be negatively impacted. From the research conducted to that period, it appeared unlikely that mean wind speeds and energy density will change by more than the current inter-annual variability, over most of Europe and North America during the present century. By the end of the 21st century there may be an increase in wintertime energy density in the north of Europe and a decline in the southeast but the uncertainty is very high. Then, suggested changes over South America may be of a larger magnitude, but also these estimates were subject to rather large uncertainty.

Talking about South America, some researchers investigated the vulnerability of wind power to climate change in Brazil (*The vulnerability of wind power to climate change in Brazil* (Pereira de Lucena et al., 2010)). The focus of the study was to analyze some possible impacts of global climate change on the wind power potential of Brazil, by simulating wind conditions associated with the IPCC A2 and B2 scenario. Results indicated that the wind power potential in Brazil would not be jeopardized in the future due to possible new climate conditions. On the contrary, authors found that the average wind velocity would increase considerably in the coastal regions in general and in the north/northeast regions of the country in particular. The results based on the climate projections showed that the Brazilian wind power generation potential could have a threefold increase in the B2 scenario and a four-fold increase in the A2 scenario for 2071-2100 as compared to the reference situation of 1961-1990. The wind potential was estimated using the projections of future wind velocities at 10 m height, which is below that of a typical commercial wind turbine. The relationship between height and wind velocity can be approximated by a logarithmic rule, in which roughness is one of the key parameters that depends on the vegetation cover. In Figures 3.22 and 3.23 are reproduced the new projected average wind velocities of A2 and B2 scenarios.

In *Climate change implications for wind power resources in the Northwest United States* (Sailor et al., 2008) the authors investigated scenarios of climate change's impacts on wind power generation potential in a five-state region within the Northwest United States (Idaho, Montana, Oregon, Washington and Wyoming). The scenarios suggested that summertime wind speeds in the Northwest may decrease by 5-10%, while wintertime wind speeds may decrease by relatively little, or possibly increase slightly. Thus under a warmed climate the wind power resource in the Northwest US may decrease by up to 40% in the spring and summer months, while in winter months the results were less consistent.

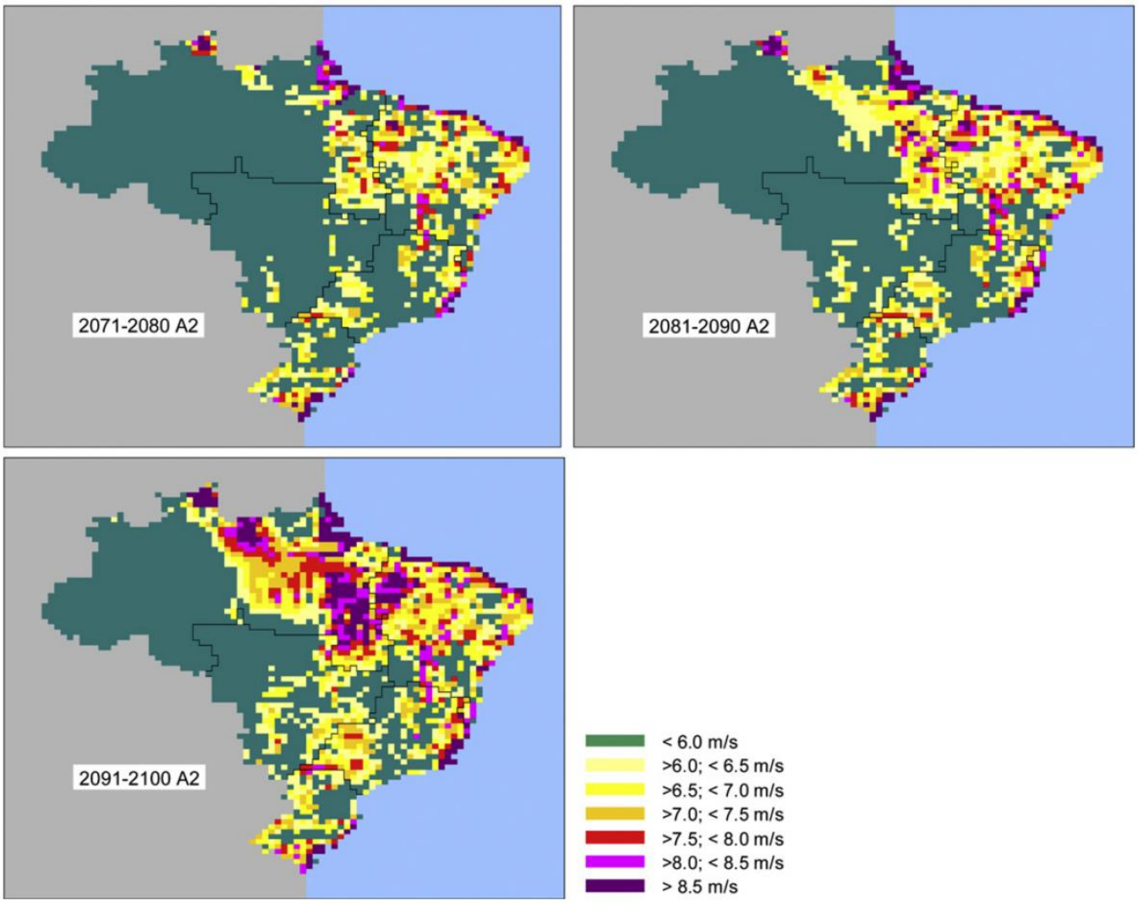

Figure 3.22 New projected average wind velocities in Brazil: Scenario A2. (Pereira de Lucena et al., 2010, p.907)

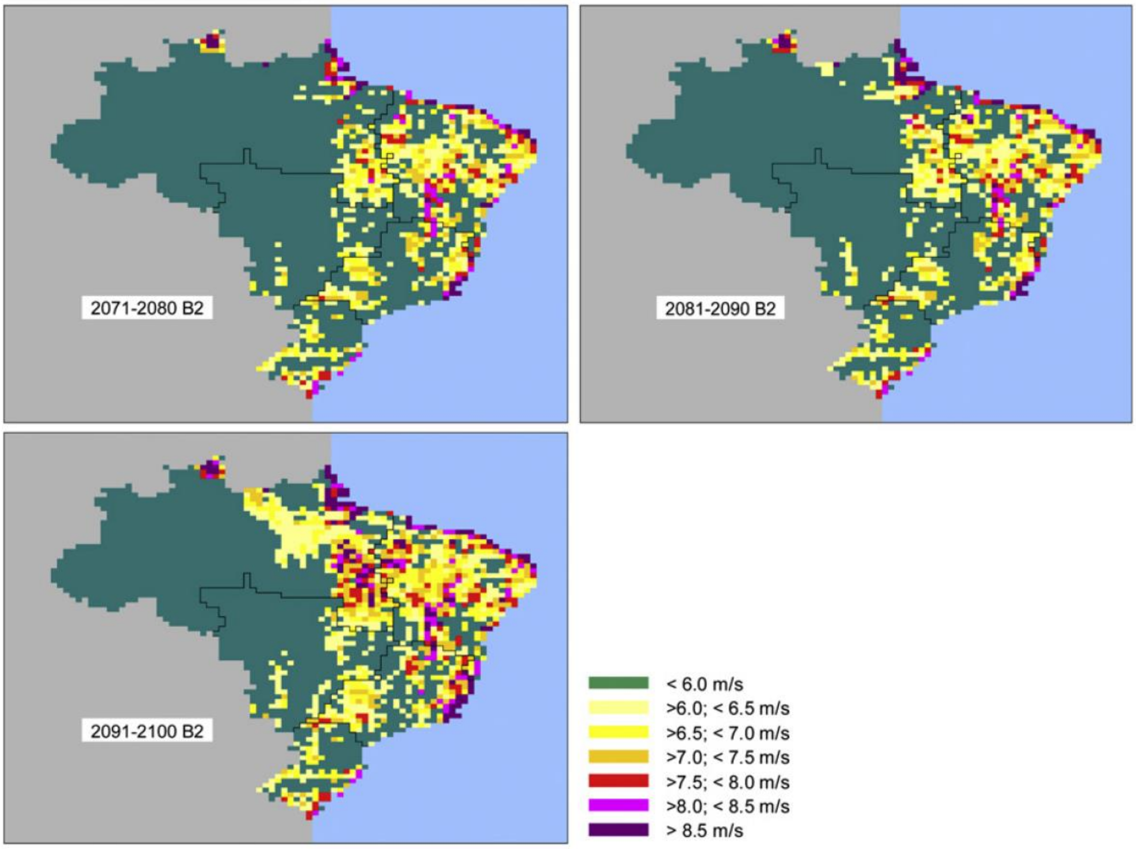

Figure 3.23 New projected average wind velocities in Brazil: Scenario B2. (Pereira de Lucena et al., 2010, p.908)

Breslow and Sailor in Vulnerability of wind power resources to climate change in the continental United States (Breslow and Sailor, 2002) investigated the potential impact of climate change on wind speeds and hence on wind power across the continental US. They used the General Circulation Model output from the Canadian Climate Center and from the Hadley Center to provide a range of possible variations in a seasonal mean wind magnitude. The results from the Hadley model suggest minimal climate change impact on wind resources, while the results from the CCC model suggest reductions in mean wind speeds in the order to 10-15%. However, the models were generally consistent in predicting that the US will see reduced wind speeds of 1.0 to 3.2% in the next 50 years, and 1.4 to 4.5% over the next 100 years.

Mideksa and Kallbekken in *Impact of climate change on the electricity market: a review* (Mideksa and Kallbekken, 2010) highlighted that whereas the research frontier has advanced significantly, there still remains a significant need for more research to better understand the effects of climate change on the electricity market. The authors focused on the areas they believed there were significant gaps: the electricity demand and the electricity supply. Discussing about electricity supply and specifically about wind power production, the researchers gave an account of some studies on the impact of climate change on the wind power potential which had been conducted for several regions:

- Clausen et al., 2007, cited in Mideska and Kallbekken, 2010, p. 4: wind power potential could increase by up to 15% in the Baltic Sea region according to the IPCC SRES A2 scenario;
- Lynch et al., 2006, cited in Mideska and Kallbekken, 2010, p. 4: climate change has a seasonally different impact on the wind power potential of Ireland. There will be an overall increase in wind speeds in winter by about 4-8% while there will be a decrease during the summer months;
- Cradden at al., 2006, cited in Mideska and Kallbekken, 2010, p. 4: UK's wind power resource. Wind speeds are expected to decrease in summer by 5% in much of the UK and by about 15% around the South-Eastern part of the Northern Ireland. Then large part of the UK would experience increased wind speed during winter;
- Bloom et al., 2008, cited in Mideska and Kallbekken, 2010, p. 4: for the Eastern Mediterranean they found that "wind speeds in 2071-2100 exhibits a general increase over land and a decrease over the sea, with the exception of a noticeable increase over the Aegean Sea".

Bioenergy

Liquid biofuels are vulnerable to the effects of weather modifications on crops used as raw materials for the production. The changes in temperature, rainfall patterns, frequency of precipitation and extreme events and level of carbon dioxide can alter the crop yield and agricultural distribution zones.

Studies like *Maize ethanol feedstock production and net energy value as affected by climate variability and crop management practices* (Persson et al., 2009) analyze the connection between weather and climatic conditions and crop management practices to evaluate the future net energy value (i.e. the output energy after all non-renewable energy inputs have been accounted for) of the biofuels production. This indicator can be a sign for the long-term sustainability of bio-ethanol production because it accounts both crop management practices and climate variability. It gives an evaluation of future grain yield for a specific crop management, but it does not indicate the measure of the future production of crops for biofuels. We can say that it gives a qualitative information rather than quantitative.

The magnitude of future biofuel endowment especially depends on the magnitude of future suitable areas for growing energy crops due to modification in climate. In this sense the authors of *The vulnerability of renewable energy to climate change in Brazil* (de Lucena et al., 2009b) evaluated the effects of climate change on the geographic distribution of biofuels crop production. The analysis of the impact of the biofuels production in Brazil was made for both ethanol and biodiesel. The work presents an estimate of the impacts of GCC on the geographic distribution of sugarcane and oil seed crops (for bioethanol and biodiesel), considering only the changes in the temperature range by region. It did not consider other variables that can influence the productivity and adaptation of these crops in determined regions, such as atmospheric CO_2 concentration and alterations in water regimes, as well as the incidence of crop pests and disease. Considering that authors did not deem many factors, the results presented may be too pessimistic for some crops, such as sugarcane and soybeans, and too optimistic for others.

- *Sugarcane.* The area planted with sugarcane should rise by 148% over the 2005-2030 period, reaching 13.9 million hectares and crop yield should increase by 7% from 77 to 82t/ha. As a result, output will expand by 161%, reaching 1.14 billion tons in 2030. Since the crops is grown in all the country's regions, even if the cultivation becomes unfeasible in some of these regions due to GCC, other regions can take up the slack, especially the Midwest, by continuing to have a temperature range favorable to sugarcane (21-38°C), along with large expanses of available land. It is possible that there will be shifts in the geographic distribution, with some regions becoming climatically unfavorable to grow sugarcane, but others becoming more favorable. Even with these possible modifications in crop distribution, GCC will not significantly affect negatively the production of sugarcane ethanol in Brazil.

- *Biodiesel.* There are various species of oilseed plants which, grow in the country that have potential as raw material to produce biodiesel. The standouts are soybeans, whose oil represents 90% of Brazil's vegetable oil output, sunflower seeds, for their oil yield, and castor beans, for the plant's resistance to drought.

  According to the results, the northeast and Midwest regions should see a substantial increase in temperature, which can affect their capacity to produce soya. Soybean output can fall or even become unfeasible in these regions due to the great temperature variations. The temperature range for growing soya (8-34°C) in the south region is expected to improve, which can offset the negative effect of climate changes in the northeast and Midwest.

  The projections for soybeans production in the country are on the whole favorable, with estimates of growth of output around 3.5 million tons yearly. The greatest projected impacts will be in the mid-south and south. The forecast production increases are between 5% and 34%.

  The results indicate that the production of biodiesels in the country can be affected negatively by GCC, mainly in the northeast, with a shift of suitable growing zones for oilseed crops to the south region. However, not all the crops are adaptable to the edaphoclimatic[1] conditions in that region, which can reduce the output of biodiesel in the country.

Wave and tidal

Ocean can provide a huge amount of energy through waves and tides. The technologies that exploit these kinds of energy resource are not so commonly used, not at the same extent as other renewable energy resources.

Wave formation results from wind energy: climate change has an effect on wind, which in turn causes indirect impacts on waves. Wind climate effects and wave generation have a nonlinear relationship and show different long trends around the globe. In some regions there has been observed a positive impact on wave energy with an increasing trend in wave height. In other regions, there has been an opposite trend, with a negative impact on wave energy owning to a decrease in wave height.

From the study *Climate sensitivity of marine energy* (Harrison and Wallace, 2005) we can deduce the relationship between wind and wave energy. In this report the authors put a focus on UK, studying here the projected changes of future wave endowment. Wind energy depends to wind speeds on a cubic relationship. A 10% change in wind speeds could alter energy yields by 13-25%, dependent on the site and season. As ocean waves are predominately the result of

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[1] Edaphoclimatic: related to edaphology and climate. Edaphology: the study of the influence of soil on living things, especially plants ("Edaphology," n.d.)

wind action, changes in wind patterns will ultimately affect wave regimes. Like wind turbines, wave energy converters (WECs) are designed to capture energy from specific wave height, period and direction ranges. Thus there are potentially significant consequences of wave energy. Mean wave height period and wave power vary within the range of wind speed changes. Wave period varies in direct proportion with the wind speed, while wave height is more sensitive to increases in speed as might be expected from the square-relationship. A 20% rise in wind speed raises mean wave heights around 44% (over a meter on average). A 20% decrease in mean wind speed lowers available power levels by 67% while the opposite change raises them by 133%.

Oil, natural gas and coal

Oil, gas resources and coal will not be impacted by climate change, because they result from a process that takes millions of years and are geologically trapped. But climate change can affect our knowledge about these resources and the access to them. For example, climate change may facilitate access to several areas by diminishing the ice cover in the Arctic region.

A specific mention should be done for coal. The study *Climate-proofing energy systems* (Williamson et al., 2009) talks about the meteorological parameters which could affect the fossil fuel endowment, focusing on coal. If average precipitation increases, coal quality could decrease due to higher moisture content of coal mines. But coal availability could increase if coal seam fires are extinguished. If average precipitation decreases, coal availability could decrease due to higher probability of coal seam fires.

3.2.2.2 Impacts of water changes on energy resources

Table 3.9 Projected impacts of water changes on energy resources

IMPACT	PROJECTIONS	REFERENCE
RUNOFF	Projections: 2050. Reference period: 1900 - 1970 • +10-40% in eastern equatorial Africa, La Plata basin, high-latitude North America and Eurasia • -10-30% in southern Africa, southern Europe, the Middle East, mid-latitude western North America	(Milly et al., 2005)
	From 44854 bcm (in 2010) to 52829 bcm (in 2100)	(MIT, 2014)

Water is an energy resource and, to be more accurate, water is a non-renewable energy resource. Analyzing the energy system, the water component must be placed logically in the category energy resource. As we have already said many times, water, as energy resource, is particular and important, because it has a strong correlation with all the components of an energy system, and for this reason we consider it as an independent entity.

Water perturbs various units that constitute the energy system, included energy resources, even if it is itself an energy resource. But specifically, water system influences the endowment of water for hydropower generation. Hydropower plants depend on the hydrological cycle and the availability of water resource. Water is used for several purposes, not just for hydropower generation. Agriculture and refrigeration needs, for example, are necessities that must be taken in consideration when we would analyze the amount of water resource available for hydropower generation.

The quantity of available water for all these aims is pondered using the runoff parameter. Runoff is that part of precipitation that does not evaporate and is not transpired, but flows over the ground surface and returns to bodies of water. Water needs for agriculture, refrigeration and hydropower generation are collected from water bodies: knowing the amount of water contained in water bodies could be really useful information. Thus several researches around the world, evaluate future impacts of climate change on runoff using a variety of hydrological model.

The Working Group I of the IPCC in the first part of the AR5 (IPCC, 2013) as usual supplies projected changes for runoff for two different time scales. Global and basin-scale hydrological models obtain near term increase runoff with global warming in the Liard (Canada), Rio Grande (Brazil) and Xiangxi (China) basins, in northwestern Africa, southern Arabia and southeastern South America. They obtain a decrease for the Okavango (southwest Africa), northern Africa, western Australia, southern Europe and southwest USA (Figure 3.24).

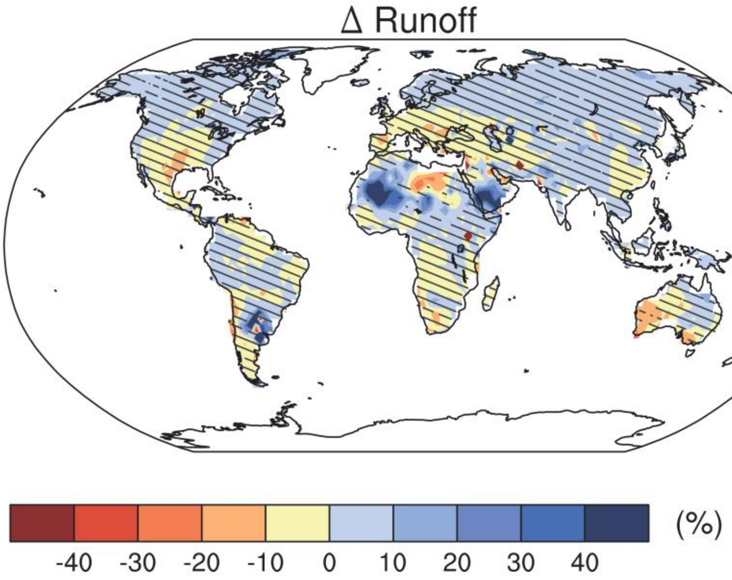

Figure 3.24 CMIP5 multi-model annual mean projected changes for the period 2016-2035 relative to 1986-2005 under RCP4.5 for total runoff (%). The number of CMIP5 models used is indicated in the upper right corner of the figure. (IPCC, 2013, p.987)

With regard to long term projections, in the AR4 21st century model-projected runoff consistently showed decreases in southern Europe, the Middle East and southwestern USA and increases in Southeast Asia, tropical East Africa and high northern latitudes. The same general features appear in the CMIP5 ensemble of GCMs for all four RCPs shown in Figure 3.25. The large decrease in runoff in southern Europe and southern Africa are consistent with changes in precipitation and warming induced evapotranspiration increases. The high northern latitude runoff increases are likely under RCP8.5 and consistent with the projected precipitation increases. Decreases in runoff are also likely in southern Europe the Middle East and southern Africa (Figure 3.25).

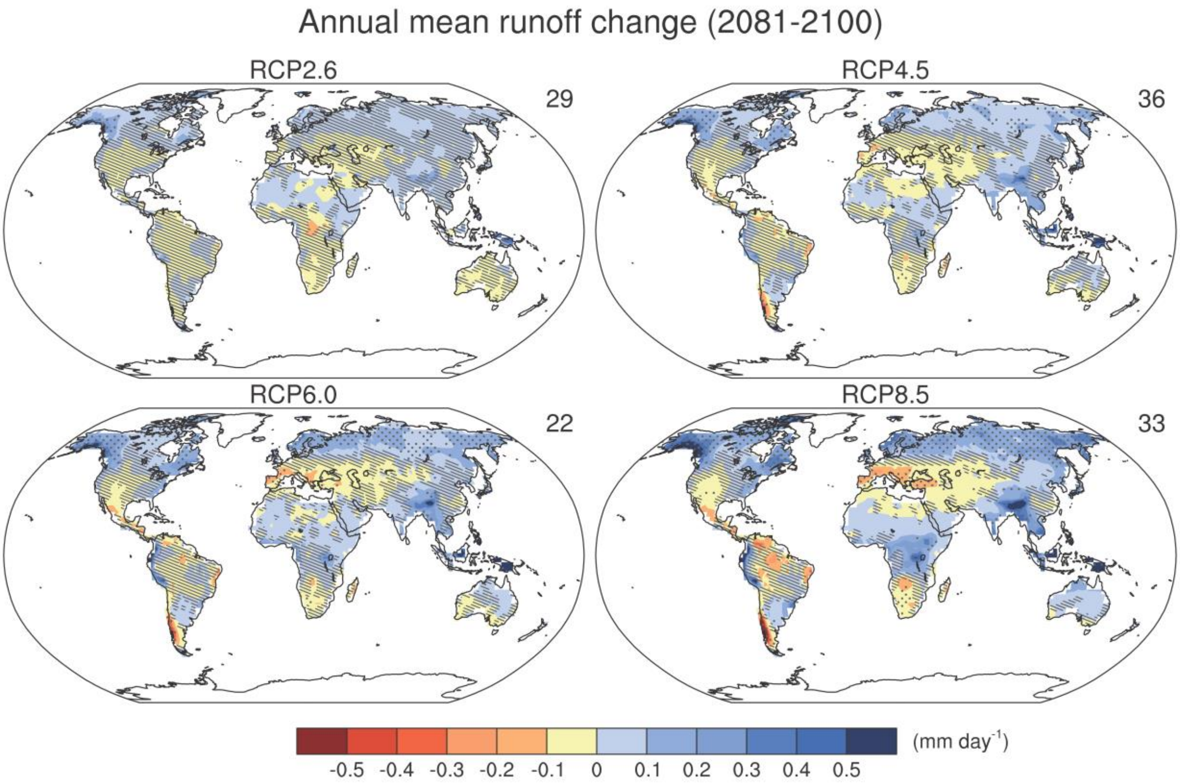

Figure 3.25 Change in annual mean runoff relative to the reference period 1986–2005 projected for 2081–2100 from the CMIP5 ensemble. The number of CMIP5 models used is indicated in the upper right corner of each panel. (IPCC, 2013, p.1081)

The paper *Effects of IPCC SRES emissions scenarios on river runoff: a global perspective* (Arnell, 2003), even if it is outdated because it took in consideration the SRES scenarios and not the RCPs, gives us an important information about catchments. By the 2020s approximately a third of all catchments will have a substantial increase in runoff, a third will have a substantial decrease, and a third will show no substantial change. By the 2050s the number with no substantial changes will reduce to between 20 and 30%, and it will fall to between 10 and 30% by the 2080s. Figure 3.26 shows the degree of consistency in the estimated direction of change in average runoff. Areas with significant decrease in runoff include much of Europe, the Middle East, southern Africa, North America and most of South America. Areas with consistent increases in runoff include high latitude North America and Siberia, eastern Africa, parts of Saharan Africa and Australia, south and East Asia.

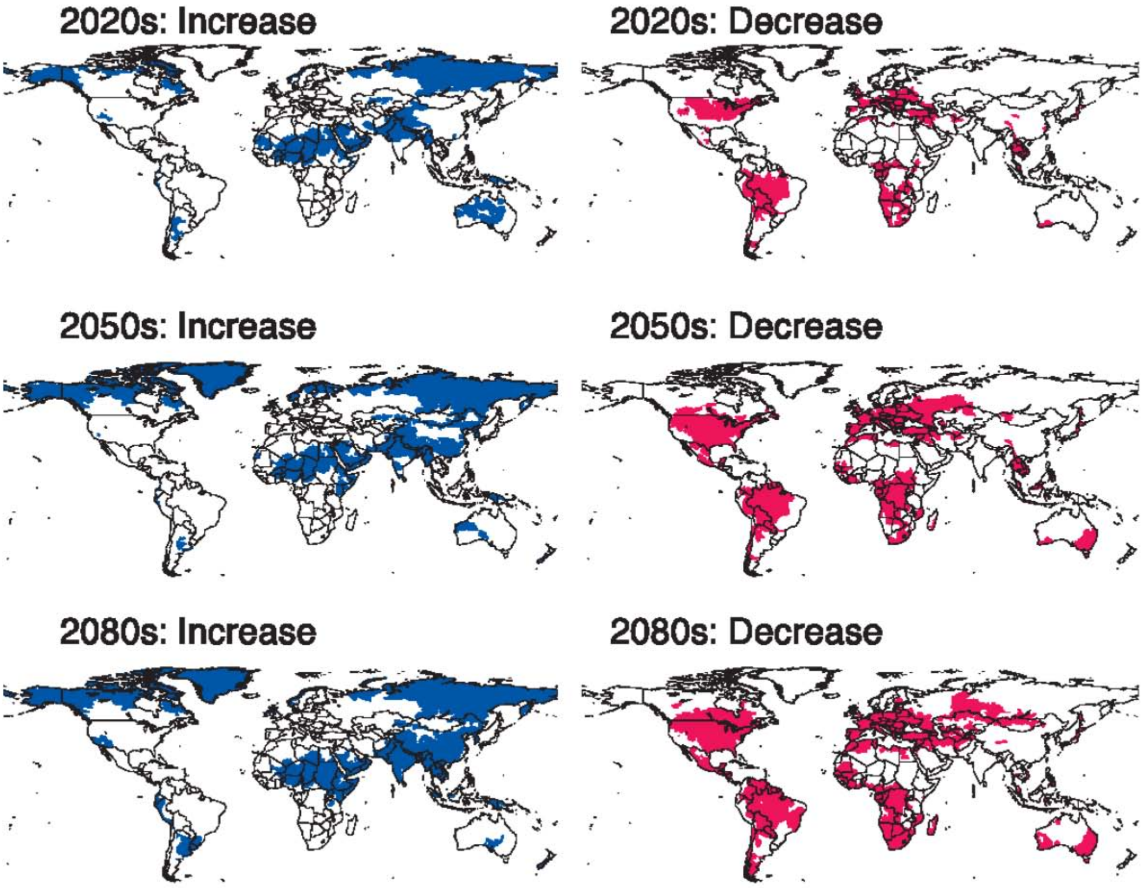

Figure 3.26 Degree of consistency in the estimated direction of change in average annual runoff across eight simulations using the A2 emissions scenario by the 2020s, 2050s and 2080s. (Arnell, 2003, p.632)

From these qualitative trends we can deduce that future changes in runoff are not univocal around the world: some regions will appreciate increases in water availability and some other decreases which depend on many factors.

Other more specific information for other regions could be noticed in other documents. For example, in the article *Global pattern of trends in streamflow and water availability in a changing climate* (Milly et al., 2005) the authors reported specific trends and ranges for several regions around the world, explaining also the causes of such changes. They used an ensemble of 12 climate models to simulate observed regional patterns of 20th century changes in streamflow and project future changes in runoff. These models projected a 10-40% increases in runoff in eastern equatorial Africa, the La Plata basin and high-latitude North America and Eurasia and a 10-30% decreases in runoff in southern Africa, southern Europe the Middle East and mid-latitude western North America by the year 2050 (see Figure 3.27). The authors stressed that in general the areas of increased runoff will shrink over time, whereas areas of decreases runoff will grow. Initial increases of runoff in the 20th century are projected to reserve in the 21st century in eastern equatorial South America, southern Africa and the western central plains of North America.

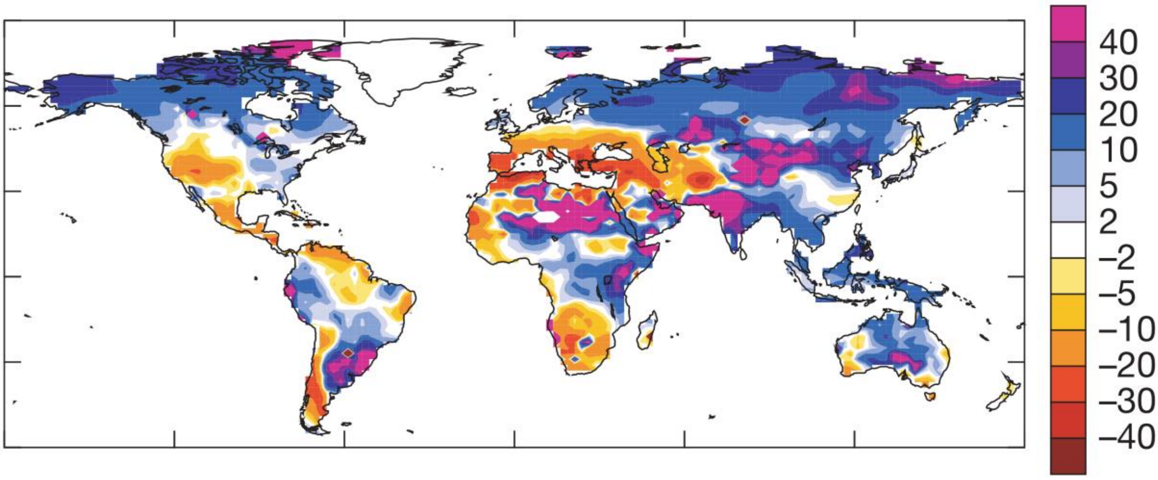

Figure 3.27 Relative change in runoff in the twenty-first century. Ensemble (arithmetic) mean of relative change (%) in runoff for the period 2041–2060, computed as 100 times the difference between 2041–2060 runoff in the SRES A1B experiments and 1900–1970 runoff in the 20C3M experiments, divided by 1900–1970 runoff. (Milly et al., 2005, p.349)

The article *Assessing climate change impacts on global hydropower* (Hamududu and Killingtveit, 2012) pointed mainly the attention on hydropower generation than hydropower endowment. Anyway, it supplied a projection of future runoff changes. Hamududu and Killingtveit used an ensemble of regional patterns of changes in runoff, computed from global circulation models (GCM) simulations with 12 different scenarios. They found that globally hydropower generation is predicted to change very little by the year 2050 for the hydropower system in operation today. Many regions will appreciate an increase in runoff and hydropower generation due to increasing precipitation, but also many others will recognize a decrease. The authors based their study on a runoff baseline data taken from the IPCC AR4. The changes reproduced in Figure 3.28 are expresses in terms of percentage variation from current runoff figures.

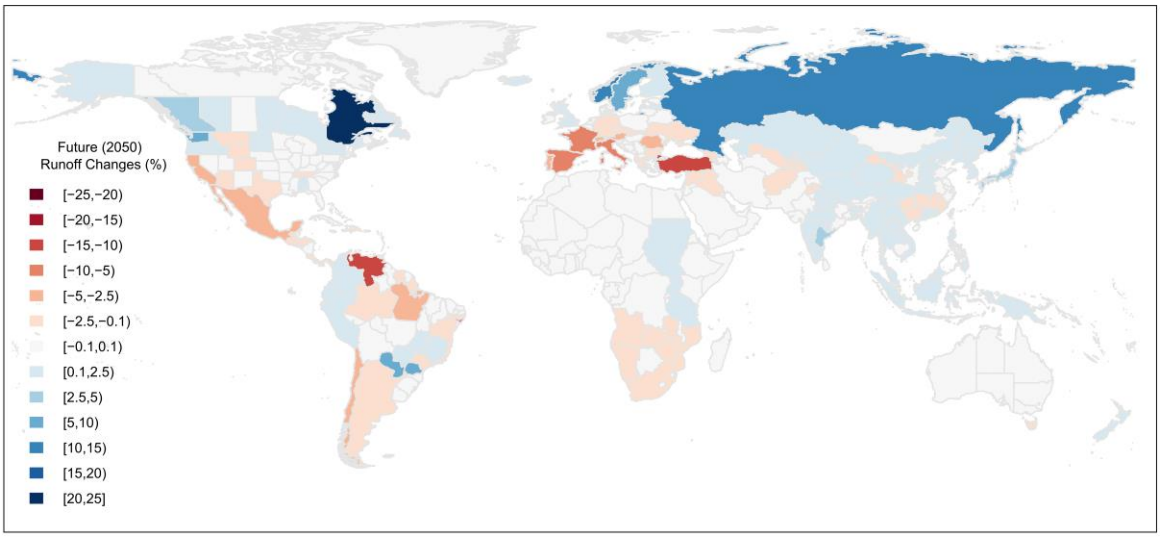

Figure 3.28 Future (2050) runoff changes (%) based on 12 GCMs under A1B scenario. (Hamududu and Killingtveit, 2012, p.312)

Based on this evaluation, the authors concluded that even if individual countries and regions may experience significant impacts, climate change will not lead to significant changes in the global hydropower generation, at least for the existing hydropower system.

Hamlet et al. produced the article *Effects of projected climate change on energy supply and demand in the Pacific Northwest and Washington State* (Hamlet et al., 2010) in which they evaluated potential changes in the seasonality and annual amount of hydropower production and changes in energy demand in a warming climate by linking simulated streamflow scenarios produced by a hydrological model. Changes in temperature and precipitation expected in the 21st century will have profound implications for the timing and volume of streamflow in the Pacific Northwest. Changes in streamflow then will have important implications for regional scale electrical energy supply. Hydropower production in the Columbia River basin is strongly correlated with modified streamflow in the Columbia River at The Dalles, Oregon. Figure 3.29 shows simulated monthly average mean flow at The Dalles, associated with 20th century climate and the three A1B and B1 scenarios. Warming will produce increased flow in winter, reduced and earlier peak flows, and systematically lower flows in summer.

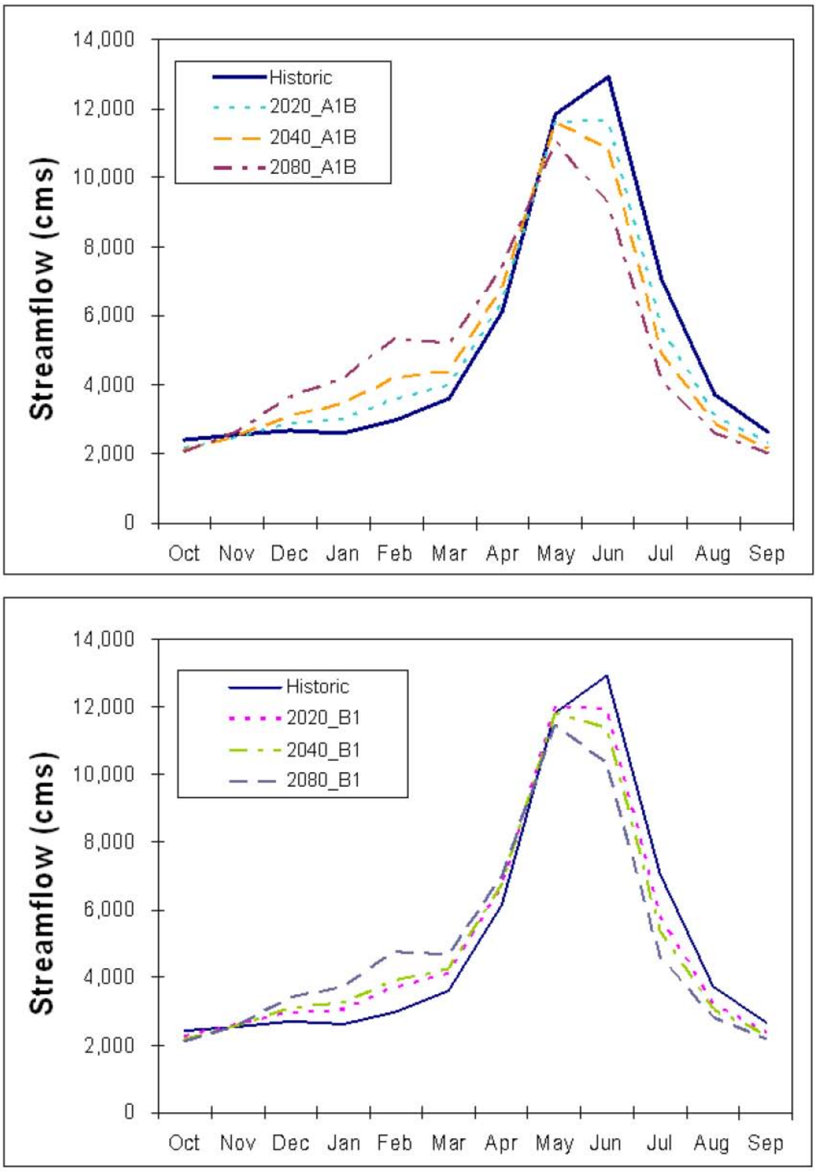

Figure 3.29 Simulated long-term mean modified streamflow for the Columbia River at The Dalles, OR, for six climate change scenarios. Top panels show results for the A1B scenario. Bottom panels show results for the B1 scenario. (Hamlet et al., 2010, p 173)

The projected increases of precipitations in cool season (October-March) and decreases in warm season in the scenarios, exacerbate the seasonal effects. On annual time scales, the effects of warming and increasing winter precipitation on streamflow are opposed. In the absence of warming, increases of precipitation in cool season would increase annual flow. In the streamflow scenarios, however, small reductions in annual flow at The Dalles (2-4% by mid-21st century) result from the combination of warmer temperatures (increased annual evaporation) and increased cool season precipitation.

The vulnerability of renewable energy to climate change in Brazil (de Lucena et al., 2009b) analyzes, as the title indicates, the vulnerability of renewable energy production in Brazil, for the case of hydropower generation and liquid biofuels production, giving a set of long-term climate projections for the A2 and B2 IPCC emission scenarios.

For the case of hydropower generation, the relevant climatic variable for the proposed analysis was the long-range outlook for the rainfall regime in the face of a possible new climate reality. The impacts of the GCC scenarios on the flow regime in the relevant Brazilian basins were assessed in two stages: the first consisted in estimating the future flows at each power plant feeding the national grid using unvaried time-series models. In the second stage, the impact of the alterations in the rainfall regime was incorporated into the projected flow series. As a general result, the flow projections for two GCC scenarios (A2 and B2) show a downward trend in the 2071-2100 period (see data in Table 3.10). In the B2 scenario the difference is greater than in the A2 scenario. The greater impact on flow occurs in the north and northeast regions of Brazil. In the Paranà Basin in the south-southeast of Brazil the impacts are not so significant. The power plants in the Paranà Basin show a seasonal positive variation in flow in the months when flow is increasing and negative in the months when it is falling. In the B2 scenario the negative impacts are even greater. If this were the case, the power plants would face an earlier dry period. The remaining basins all show an average negative impact on flow.

Table 3.10 Results for hydropower (deviation from the reference projections) (de Lucena et al., 2009b, p.884)

BASIN	AVERAGE ANNUAL FLOW	
	A2 (%)	B2 (%)
Paraná River	-2.40	-8.20
Grande	1.00	-3.40
Paranaíba	-5.90	-5.90
Paranapanema	-5.00	-5.70
Parnaíba	-10.10	-10.30
São Francisco	-23.40	-26.40
Tocatins-Araguaia	-14.70	-15.80
Brazil (SIN)	-8.60	-10.80

Note. SIN: Sistema Interligado Nacional (Brazilian Interconnected electric power system)

The Mideksa and Kallbekken paper *The impact of climate change on the electricity market: a review* (Mideksa and Kallbekken, 2010) reviewed the research on climate change impact on electricity market through both electricity demand and supply. Talking about the hydropower supply, the authors reported the results of the study of Bye (Bye, 2008, cited in Mideksa and Kallbekken, 2010, p.4). Bye analyzed the effect of climate change on supply based on hydro and wind power in Northern Europe. He reported that river inflow and wind speed would increase by 11% and 1% respectively, between 2001 and 2040. This would raise the supply of power by 1.8% relative to 2001.

In contrast to the studies mentioned until now, the report *2014 Energy and climate outlook* (MIT Joint Program on the Science and Policy of Global Change, 2014) of the Massachusetts Institute of Technology includes a global estimation of future total water supply, divided into runoff, withdrawal and evaporation. The total water supply in 2010 was 46398 billion cubic meters (bcm) while in 2100 it will be 54454 bcm. The total runoff will change from 44854 bcm in 2010 to 52829 bcm in 2100 according to the projections. These estimations consider total runoff (generated from precipitation), groundwater recharge, withdrawals, return flows and water consumption (withdrawals that evaporate or not directly return to the basins).

3.2.3 Expected impacts on energy demand

The evaluation of climate change's impacts on energy demand is fundamental for the management of the entire energy system. It is so important because it gives us an estimate of future energy consumption, which affects consequently the energy generation and the energy endowment. Once it was not considered so significant because an alteration of energy demand was reflected into a simple increase or decrease of energy supply. But now we acknowledge that, for example, a rise of surface air temperature in summer will lead to an increase in electricity consumption for space cooling, which needs an increment of electricity generation (affected by climate change) that requires more energy resources, which in turn are influenced by the changes in climate. Thus the relevant impacts of climate change into the energy system are not restricted to the resource and supply side.
Besides space cooling there are other requirements which are altered by future climate changes. The amount of energy consumed in residential, commercial and industrial buildings for space heating is one of them. Others are the energy for water heating, commercial refrigeration, industrial process cooling and performance, agriculture and desalinization. Furthermore, water requirements are altered by climate change: the water demand in industry and agriculture will vary cause of temperature and water changes.

This section of the assessment considers temperature rising and water changes as principal origins of impacts. Temperature increase will alter the energy consumption in buildings (heating and cooling demand), in industry and in agriculture. In addition, temperature rise will change water use in industrial processes and water withdrawal in the agricultural sector. Changes in water properties, as temperature and availability, will then vary the final use of energy in almost all sectors, although we will concentrate only on the use of energy for water treatment.

3.2.3.1 Impacts of temperature changes on energy demand

Table 3.11 Projected impacts of temperature changes on energy demand

IMPACT	PROJECTIONS	REFERENCE
HEATING DEMAND	+0.8% a year between 2000 and 2030, and after slowly decrease -34% worldwide by 2100	(Isaac and van Vuuren, 2009)
COOLING DEMAND	From 1900 kWh (in 2000) to 4800 kWh (in 2100). +7% a year between 2020 and 2030. Then +1% a year to the end of the century +70% greater than projected demand without climate change	(Isaac and van Vuuren, 2009)
INDUSTRY	U.S. energy consumption per unit of industrial production: +0.0127% per increase in 1 HDD or +0.0032% per increase of 1 CDD Annual basis: -6.2% energy demand (a saving of 0.0422 EJ)	(Wilbanks et al., 2008)
	Use of water: +45% from 763 bcm (2010) to 1098 bcm (2100)	(MIT, 2014)
AGRICULTURE	-10% from 1551 bcm (2010) to 1389 bcm (2100)	(MIT, 2014)
	Water withdrawals (B2 scenario): from 2498 bcm (1995) to 2341 bcm (2025), to 2256 bcm (2055) and 2211 bcm (2075)	(Alcamo et al., 2007)

As for other sectors of the energy system, there are not so many documents in literature which regard future impacts of climate change on energy demand on a global scale. The majority of existing studies focuses on the effects at local level, because generally climate impacts on energy use vary across regions. Nonetheless hereinafter some data and trends of heating and cooling demand, industry and agriculture use are reported.

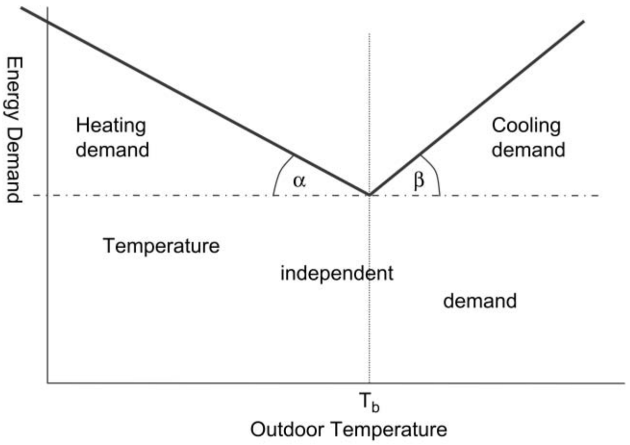

Figure 3.30 Temperature Dependence Pattern based on a degree day approach. (Hekkenberg et al., 2009, p.1799)

Heating and cooling demand in buildings

The total energy demand for heating and cooling for buildings depends on outdoor temperature. A lot of empirical studies come to the same conclusion, that the energy demand depends on a temperature dependence pattern (TDP), which presents a U-shaped fashion (see Figure 3.30). This U-shaped TDP suggests that climate change may have ambiguous consequences for future energy demand at global level, as increasing outdoor temperatures could generally reduce heating demand and could increment cooling demand.

The assessment of the impacts of temperature variations can be conducted using the concept of heating and cooling degree-days, even if energy consumption's projections using degree day calculations can be fairly coarse. This method is appropriate only if the building use and the efficiency of the equipment remains constant. Furthermore, its application is limited because it considers only the effect of dry bulb temperature, which is extremely incorrect for cooling loads, because the load is dependent on both sensible and latent heats.

The article *Modelling global residential sector energy demand for heating and air conditioning in the context of climate* change (Isaac and van Vuuren, 2009), is one of those few documents which consider globally the impacts of climate change into the energy sector. In this paper the authors attempted to describe residential heating and cooling demand in the context of climate change at global scale. They used relatively simple relationships to describe heating and cooling demand and explore the impacts of climate change on this simulated energy demand.

The two effects of temperature increase on energy use in buildings are clear, as energy use for heating decreases and energy use for cooling increases. On the other hand, it is not so obvious whether the sum of energy use for heating and cooling will increase or decrease, even because worldwide reductions and increments of energy demand are not homogeneous.

The authors used simply functions based on Heating and Cooling Degree Days (HDDs and CDDs) to estimate the energy demand of buildings. They as well used other parameters, like the Unit Energy Consumption (the average energy consumption per household using air condition), the penetration of air conditioners in households and the efficiency improvements to assess in the best way the future energy consumption in buildings. They used future scenarios which describe the regional demand and supply as a function of change in population, economic activity and energy efficiency. The results of their research on residential energy demand are easily visible in the diagram of Figure 3.31.

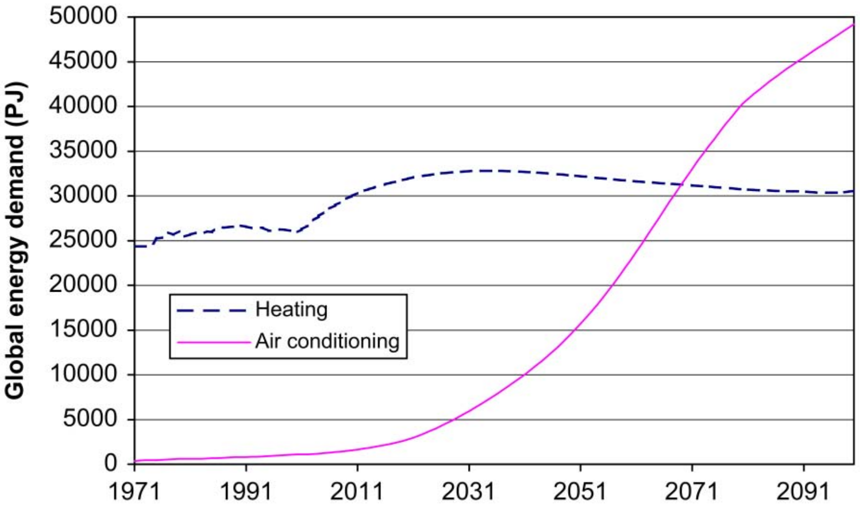

Figure 3.31 Modeled global residential energy demand for heating and for air conditioning in a reference scenario. (Isaac and van Vuuren, 2009, p.513)

We could observe that global energy demand for heating will increase by 0.8% a year between 2000 and 2030 due to increasing income and population and after it will decrease slowly due to level off of population growth and climate change. The regions with the highest heating energy demand are Western Europe, USA, Russia and China. In Europe final energy demand is projected to start decreasing in 2010 by 0.7% a year. In Russia demand is projected to start decreasing in 2020 by 0.6% a year. These declines will be the result of a stabilization or decline of the population, a decline of heating intensity and a warming climate. The projected trend is consistent with the fact that heating energy demand has been more-or-less constant over the past decades in Europe. In the USA and China, heating energy demand will increase throughout the century. The gradual 0.7% a year increase in demand in the USA will be driven by rising population and housing areas, while in China heating intensity is projected to go up too, compensating for the decrease in population predicted after 2030. Most of the growth in energy demand in China will occur before 2040, at a rate of 1.7% a year. The trends of these countries and for other are noticeable in the chart of Figure 3.32. The expected reduction in heating energy demand by 2100 worldwide is 34%.

During the 21st century the penetration of air conditioning will increase extremely rapidly in most developing regions, driven by an increase in income levels and in numbers of CDDs. The UEC (Unit Energy Consumption) is the highest in the warmest regions with relatively high-income levels (USA and Europe). It is expected that it will increase from 1900 kWh in 2000 to 4800 kWh at the end of the century, due especially to climate change. In India and South East of Asia UEC is projected to increase to much higher levels, around 13000 kWh due to warm climate. As a result of the trends, electricity demand for air conditioning is projected to increase rapidly. Globally the rate of increase will be at its peak between 2020 and 2030 at 7% per year, then it will be reduced to 1% a year by the end of the century. The result will be a cooling energy demand 40 times larger in 2100 than in 2000. The demand will be about

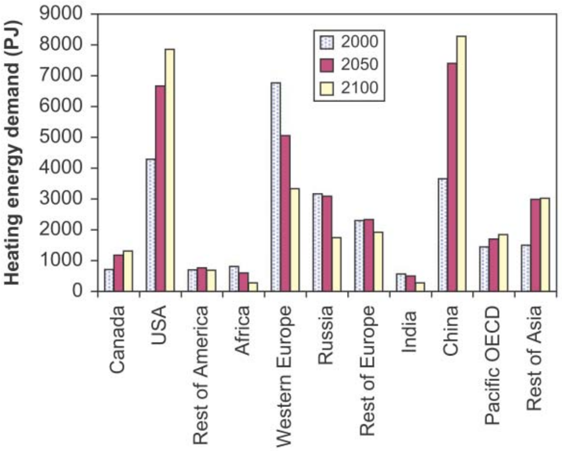

Figure 3.33 Modeled regional residential energy demand for heating in the years 2000, 2050 and 2100 (reference scenario). (Isaac and van Vuuren, 2009, p.514)

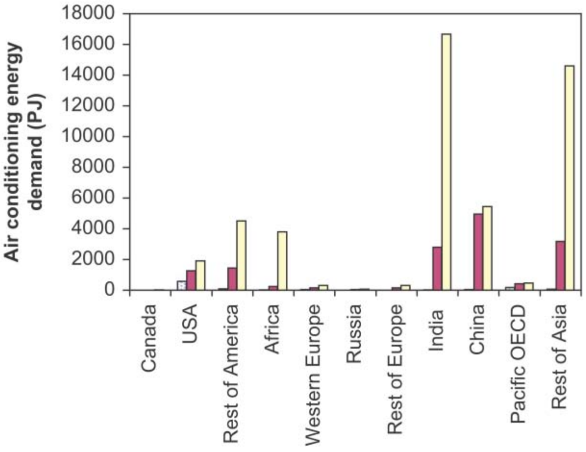

Figure 3.32 Modeled regional residential energy demand for air conditioning in the years 2000, 2050 and 2100 (reference scenario). (Isaac and van Vuuren, 2009, p.514)

70% greater than projected demand without climate change. The chart of Figure 3.33 describes the trends for future cooling demand for specific countries or regions.

Ruth and Lin in *Regional energy demand and adaptation to climate change: methodology and application to the state of Maryland, USA* (Ruth and Lin, 2006) explored the potential impacts of climate change on natural gas, electricity and heating oil use by the residential and commercial sectors in the state of Maryland, USA. The authors did not explore the impacts of climate change at global scale and neither at a country level: they concentrated on a single state, choosing Maryland because the state's energy use infrastructure has evolved to deal both with high cooling demands during summer months and heating demands during winter. The results indicate that climate change will induce a comparably small signal on future energy demand for Maryland. However, there is the need to highlight that the paper specifically concentrated on the potential impacts of climate change on energy demand in the residential and commercial sectors of Maryland, but explored also demand changes in the broader context of economic and population changes. The projections they made are strongly influenced by the economic and populations parameters, but nevertheless they extrapolated the percentage change attributable to climate change from the overall projections.

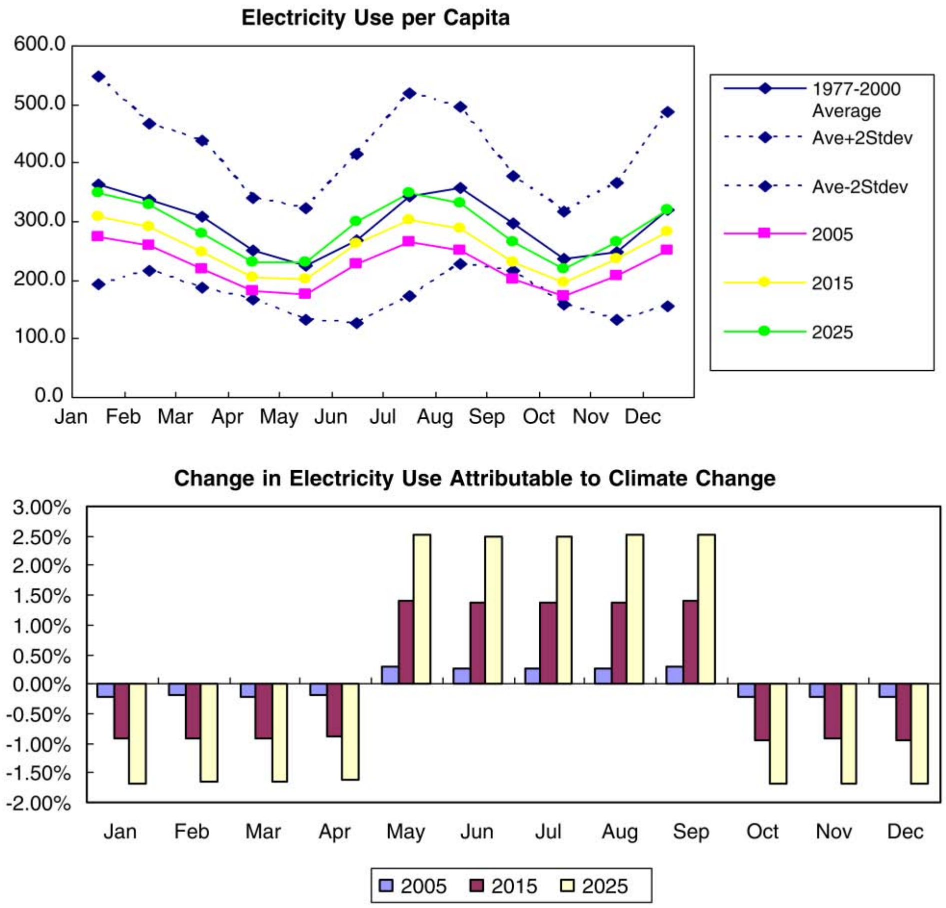

Figure 3.34 Electricity use per capita and percentage change attributable to climate change. (Future electricity price is assumed to be equal to the average historical price.) (Ruth and Lin, 2006, p.2828)

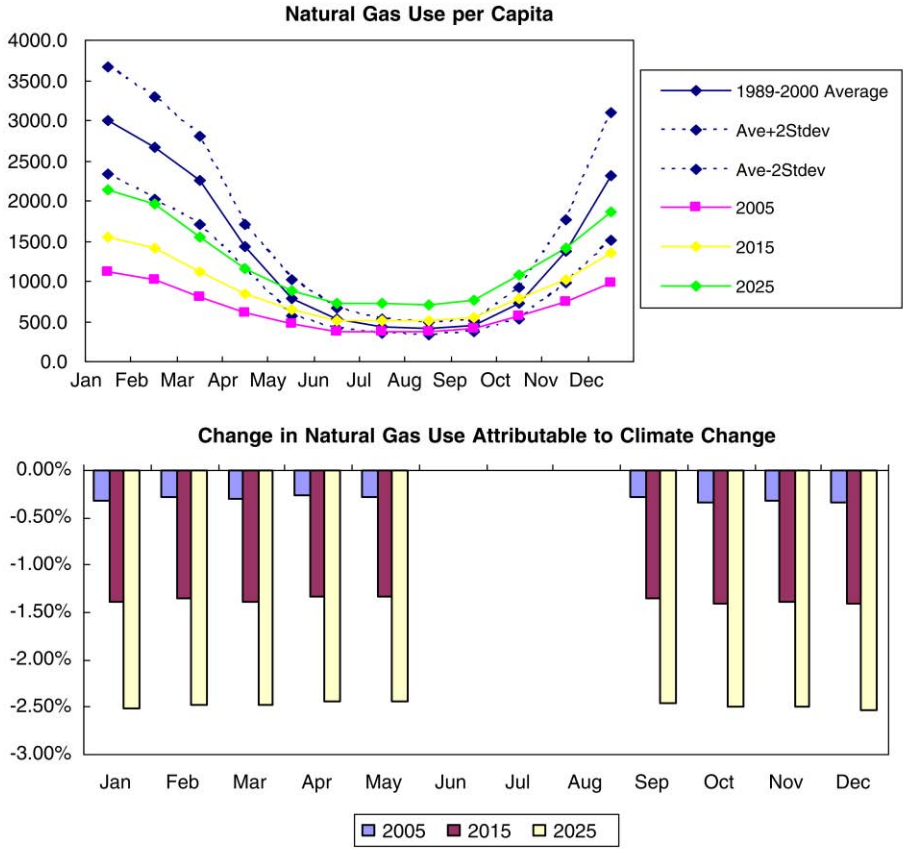

Figure 3.35 Natural gas use per capita and percentage change attributable to climate change. (Future natural gas price is assumed to be equal to the average historical price.) (Ruth and Lin, 2006, p.2830)

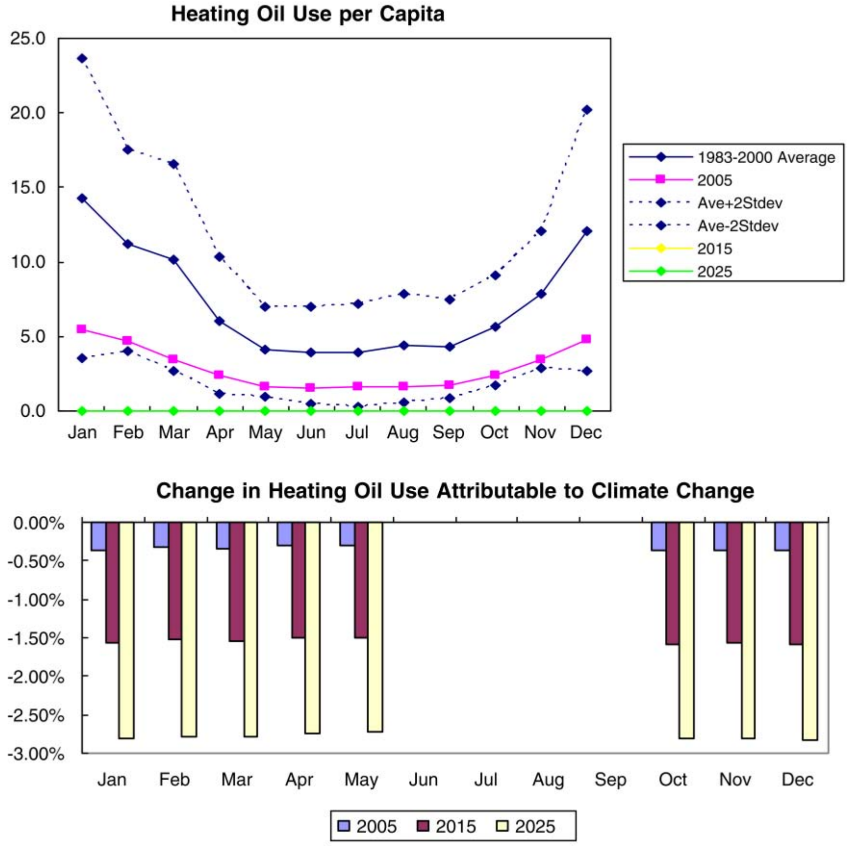

Figure 3.36 Heating oil use per capita and percentage change attributable to climate change. (Future heating oil price is assumed to be equal to the average historical price.) (Ruth and Lin, 2006, p.2831)

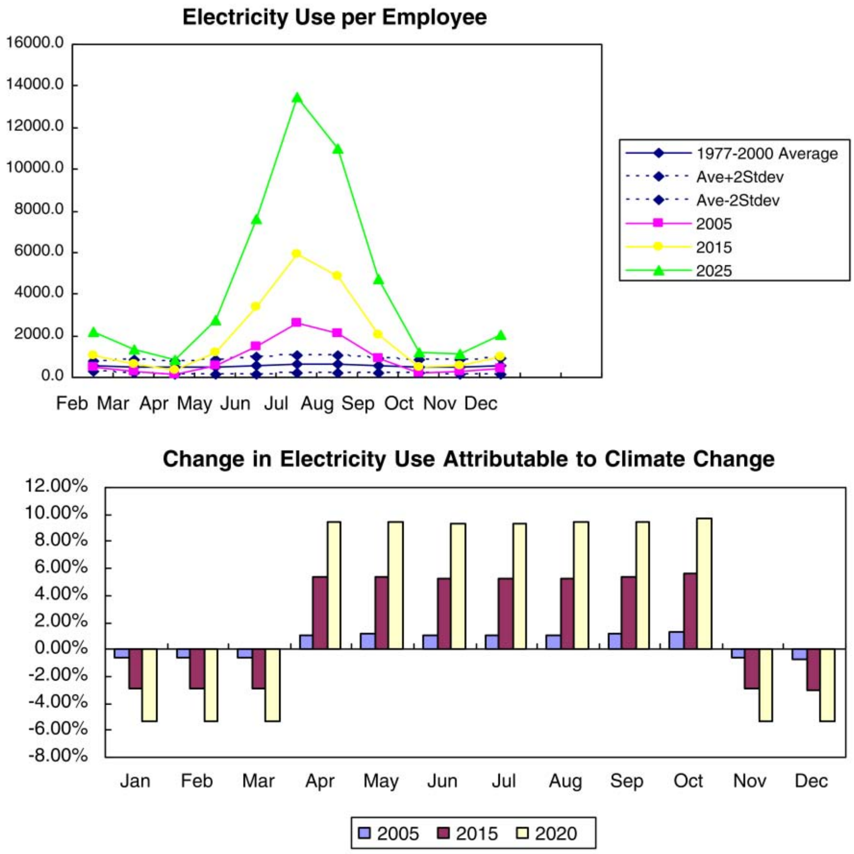

Figure 3.37 Electricity use per employee and percentage change attributable to climate change. (Future electricity price is assumed to be equal to the average historical price.) (Ruth and Lin, 2006, p.2831)

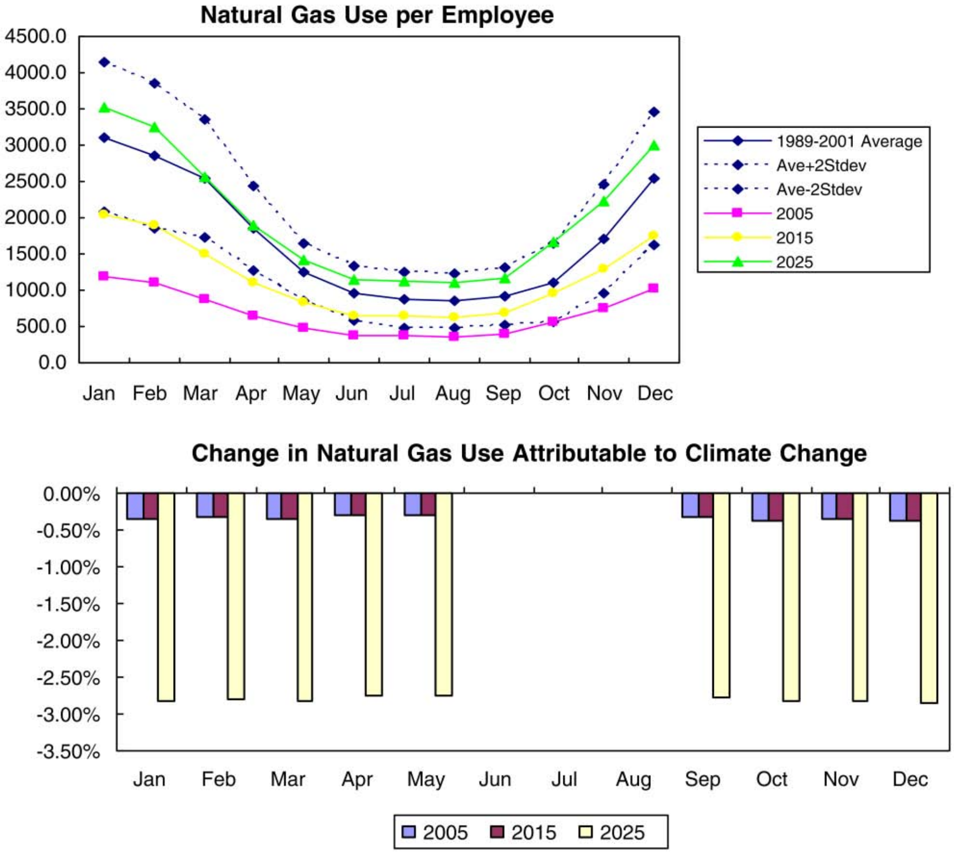

Figure 3.38 Natural gas use per employee and percentage change attributable to climate change. (Future natural gas price is assumed to be equal to the average historical price.) (Ruth and Lin, 2006, p.2832)

As said they investigated the potential impacts on electricity, natural gas and heating oil use by the residential and commercial sectors. They realized specific graphs to show projections of electricity, natural gas and heating oil use per capita, electricity and natural gas use per employee and their respective percentage changes attributable to climate change. These charts are illustrated from Figure 3.34 to Figure 3.38.

The paper *Impact of climate change heating and cooling energy use in building in the United States* (Wang and Chen, 2014) quantified the impact of climate change in the energy consumption by heating and cooling systems in buildings in the US. This study used the HadCM3 Global Circulation Model (GCM) to generate weather data for future typical meteorological years, such a 2020, 2050 and 2080, for 15 cities in the U.S. on the basis of three CO_2 scenarios. Two types of residential buildings and seven types of commercial building were simulated for each of the 15 cities. This study found that the impact of climate change varied greatly by geographical location and building type. However, there would generally be a net increase in source energy consumption by the 2080s, but it may decrease slightly in some locations.

This study varies from others which use the degree day method with future weather data to determine the impact of climate change on building energy consumption. The degree day method can provide a quick estimate of the impact of climate change on buildings because it considers only the outdoor temperature as element of impact. It does not consider the solar radiation, the humidity and building characteristics such as thermal mass, which largely affect the energy demand of a building. For these reasons they used a sophisticated energy simulation program – EnergyPlus – for studying the impact of climate change on energy use in buildings, because this program has integrated modules for zone, system and natural ventilation calculations. They principally concluded that the majority of the cities located in warm and hot climate zones would experience a net increase in source energy for cooling and heating by the 2080s, while cities in cold climate zones would experience a net reduction on source energy use.

The report *Effects of climate change on energy production and use in the United States* (Wilbanks et al., 2008) analyzed among other things the energy demand in residential and commercial buildings. The report summarized current knowledge about potential effects of climate change on energy demand in the United States without exploring the methods used in the various studies to elaborate the consumption projections. The authors mainly focused on the effects of climate change on energy consumption in buildings, emphasizing space heating and space cooling. They resumed some national and regional studies finding the effects of climate change on residential and commercial space heating and cooling.

Hereinafter the displayed data are deduced only from one document: *A discrete-continuous choice model of climate change impacts on energy* (Mansur et al., 2005). The impacts of climate change were calculated establishing an impact of 1°C increase in January temperatures in 2050. The impact on the consumption of energy in residential heating was relatively modest. It predicted a 2.8% reduction of residential electricity consumption for electricity-only consumers, a 2% reduction of residential electricity consumption for gas consumers and a 5.7% reduction of residential electricity consumption for fuel oil customers. Then Mansur et al. projected that a 1°C increase in January's temperatures would produce a reduction in electricity consumption of about 3% for electricity for all-electric customers. In addition, the warmer temperatures would reduce natural gas consumption by 3% and fuel oil demand by a sizeable 12% per 1°C. As regards residential space cooling, the authors projected that when July's temperatures were increased by 1°C, electricity-only customers increased their electricity consumption by 4%, natural gas customers increased their demand for electricity by 6% and fuel oil customers brought 15% more electricity. Finally, the projected changes on commercial space cooling when January's temperatures were increased by 1°C show an increase of electricity consumption of 4.6% for electricity-only customers, a decrease of 2% for natural gas customers and an increase of 13.8% for oil customers.

Industry demand

It is not thought that industrial energy demand is particularly sensitive to climate change. Industrial facilities devote only about 6% of their energy use to space conditioning. This fact does not mean that industry is not sensitive to climate, or even that energy availability as influenced by climate or weather does not affect industry.

Most of the energy used in industry is used for water heating: energy use would likely decline in industry if climate and water temperatures become warmer. Then, electrical outages, most of the times caused by extreme events, cause many interruptions every year which provoke huge economic damages.

The report *Effects of climate change on energy production and use in the United States* (Wilbanks et al., 2008) cited the study of Considine, 2000, *The impacts of weather variations on energy demand and carbon emissions*, in which the author econometrically investigated industrial energy use U.S. data based on Heating Degree Days and Cooling Degree Days (in Fahrenheit) and calculated that U.S energy consumption per unit of industrial production would increase by 0.0127% per increase in 1 HDD or by 0.0032% per increase of 1 CDD. On an annual basis with a 1°C of temperature increase (1.8°F), there would be a maximum of 657 fewer HDD per year and 657 more CDD (in Fahrenheit basis). This would translate into 6.2% less net energy demand in industry or a saving of 0.0422 EJ.

The Massachusetts Institute of Technology in its *2014 Energy and climate outlook* (MIT Joint Program on the Science and Policy of Global Change, 2014) paid a specific attention on the impacts of climate change on water resources and projecting future changes in water consumption in the domestic sphere, industry sector and agriculture. As regards the industrial use of water, they are expecting an increase of the use by almost 45% from 763 billion cubic meters (bcm) in 2010 to 1098 bcm in 2100 (see Figure 3.39).

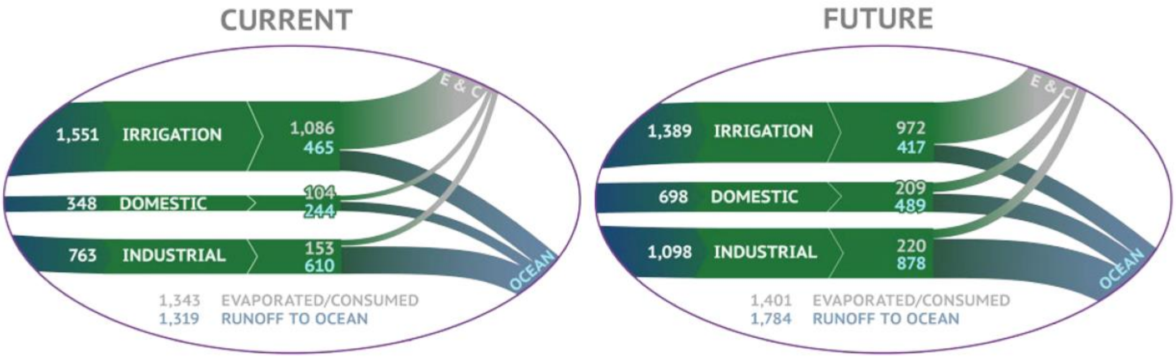

Figure 3.39 Current and future global withdrawal uses of water (in 2010 and 2100), in billion cubic meters. (MIT Joint Program on the Science and Policy of Global Change, 2014, p.15)

Agriculture demand

As already reported, agriculture energy use falls into five main categories: equipment operations, irrigation pumping, embodied energy in fertilizers and chemicals, product transport, drying and processing. A warmer climate implies increases in the demand for water in irrigated agriculture, but also in the use of energy for pumping. However, no accurate estimates of these effects could be found in available literature.

Projections of future water withdrawal in agriculture could be found in *2014 Energy and climate* outlook (MIT Joint Program on the Science and Policy of Global Change, 2014) and also in *Future long-term changes in global water resources driven by socio-economic and climate changes* (Alcamo et al., 2007). The MIT projected a future irrigation need of about 1389 bcm in 2100 from 1551 bcm in 2010 (reduction of the 10%). Alcamo et al. instead reported the global projections of agriculture water withdrawal for A2 and B2 scenarios. Agriculture water withdrawals for A2 will change from 2498 bcm in 1995 to 2366 bcm in 2025, 2282 bcm in 2055 and 2246 in 2075. As regards the B2 scenario, the withdrawal will vary from 2498 bcm in 1995 to 2341 bcm in 2025, 2256 bcm in 2055 and 2211 bcm in 2075. The two trends show a decrease of water withdrawal for agriculture, and they are comparable because they belong to the same order of magnitude.

3.2.3.2 Impacts of water changes on energy demand

Table 3.12 Projected impacts of water changes on energy demand

IMPACT	PROJECTIONS	REFERENCE
DOMESTIC USE	+100% from 348 bcm (2010) to 698 bcm (2100)	(MIT, 2014)

Water system is constituted by varied elements. The consequences of climate change could be notified in the water system and all its elements, as we have highlighted for oceans and cryosphere. But water system is formed also by freshwater resources, which we can locate on the surface (lakes, rivers and so on) and in the ground (aquifers). Surface and ground water convert themselves nearly entirely into runoff and the remaining part evaporates or is consumed. These processes occur because humans withdraw water resources from global water sources to meet some needs, as irrigation, industrial and domestic need. The water used for these needs is defined as withdrawal water. As we can read in *2014 Energy and climate* outlook (MIT Joint Program on the Science and Policy of Global Change, 2014), water resource experts estimated that only 10% of total water supply (as freshwater flow) is actually available for human withdrawal. The current total global water supply is estimated at 46398 bcm (see Figure 3.40), the withdrawal at 2662 bcm and the consumption at 1544 bcm: thus the use of water is about the 30% of the realistically available global supply.

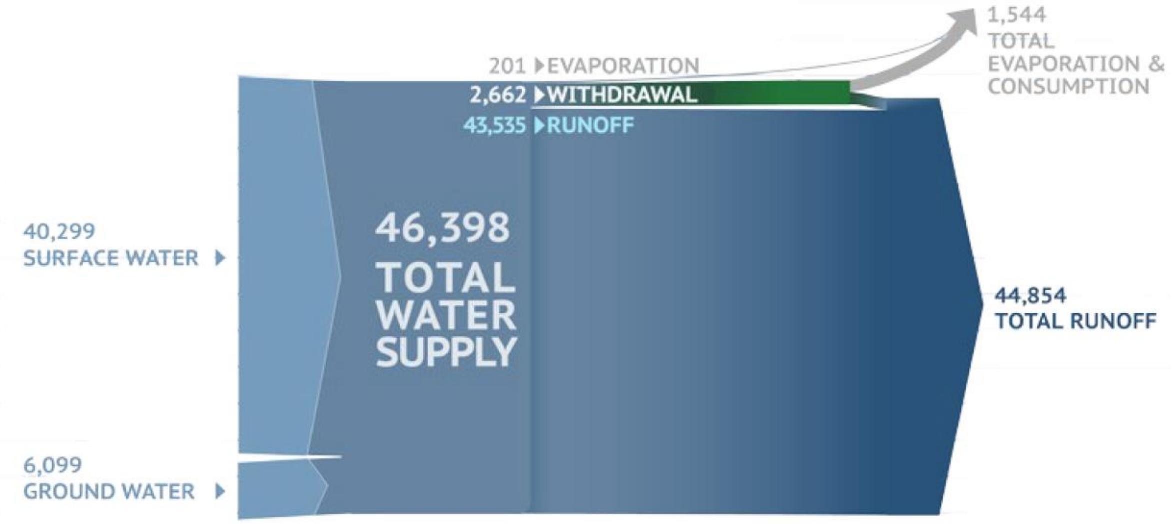

Figure 3.40 Current global water sources (2010), in billion cubic meters. (MIT Joint Program on the Science and Policy of Global Change, 2014, p.15)

Comparing Figure 3.40 with Figure 3.41, which show the 2100 global water sources and use, the global freshwater supply is projected to increase by 17% from 46398 bcm to 54454 bcm as direct result of projected increased precipitation over land. On the demand side, total water withdrawals are expected to increase from the current levels of about 2700 bcm to 3200 bcm in 2100 (19% of increase). Looking at Figure 3.39 we can appreciate that domestic use of water is projected to double from 348 bcm to 698 bcm in 2100. Then we can also distinguish between consumption of water (the amount lost to evaporation or consumed and not returned to the basin) and withdrawals, which include consumption plus return flow. Withdrawals and consumption as a percentage of total annual flows can provide a misleading picture of the adequacy of water resources, because location and timing of flows is important. Similarly, the seasonality of precipitation often means the timing of flows does not match needs.

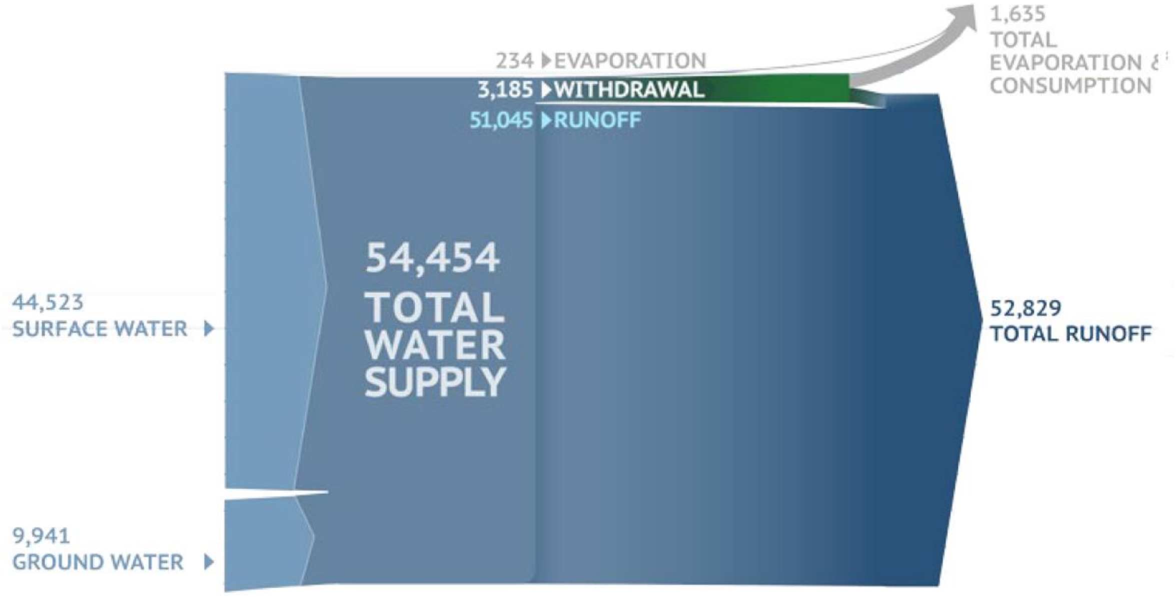

Figure 3.41 Future global water sources (2100), in billion cubic meters. (MIT Joint Program on the Science and Policy of Global Change, 2014, p.15)

The water demand for domestic use, agriculture and industry will change in future due to climate change as we have seen. The supply of freshwater resources requires a cert amount of energy and if water system is projected to be modified by climate change, consequently also the energy demand will vary to supply freshwater. Thinking about domestic use, it will double in 2100 according to the MIT assessment. By 2100 MIT scenarios, despite abundant global supply, show increased water stress in parts of India, China, Pakistan, Turkey, North Africa, South Africa and U.S.

To guarantee the necessary supply of freshwater in these regions will economically and energetically cost. Some regions around the world are already suffering this problem, like Canary Islands, the Indus River basin and California. For example, a desalination plant is under construction in Carlsbad, California, to provide about 7% of the San Diego region's water ("Desalination Plant," n.d.): in any case the plant entails high costs, environmental concerns and challenges of piping water inland as well as an increasing energy consumption. Some other areas, as the Indus River basin in India and Pakistan, may experience substantial shortages of surface water. In this region total withdrawal will exceed the amount of available surface water by 2100. That condition would imply an unsustainable situation and would need a fulfillment of water requirements by a transformation of current management practices in the region, including the water supply provided by groundwater extraction.

Currently there are not available specific projections about this subject at global level and neither at regional scale. This problem is undeniable and the trends are well-rendered, but there is no specific literature about.

3.2.4 Expected impacts on energy supply

We can say that the evaluation of climate change's impacts on the energy supply system is the main task of the first part of this study and in general of the assessment of climate impacts on energy system.

The energy supply system is that part of the energy system which converts primary energy into a form that can be used by consumers. In this analysis we take in consideration electricity as kind of energy used by consumers. We can not affirm that the energy supply system, formed by all the facilities that generate electricity, transmit and distribute it to the users, is the energy system's portion most influenced by climate change. But it is undeniable that the impacts are huge and that the sector has a strategic importance in the complexity of the energy system.

As already explain in the previous sections of the thesis, the description of the expected impacts on energy supply system is structured in a precise way. All the impacts should be attributed to climate change because climate change as a whole alters the energy supply and the related facilities. Nevertheless, we consider that the impacts are attributable to more sections which constitute the natural-energy system, as we can notice in Figure 2.1 at page xx and Figure 2.3 at page xx. The arrow corresponding to temperature indicates the analysis of the efficiency of supply facilities, whereas the arrow corresponding to water indicates the assessment of the refrigeration systems of the facilities. The climate change arrow then treats the mitigation projections. So the links between energy supply and other sections point out particular correlations between energy generation and natural environment.

3.2.4.1 Impacts of temperature changes on energy supply

Table 3.13 Projected impacts of temperature changes on energy supply's efficiency

IMPACT	PROJECTIONS	REFERENCE
SOLAR POWER	The increase of air temperature can modify the efficiency of photovoltaic cells and ultimately reduce the PV electric generation	(Fidje and Martinsen, 2006)
THERMAL PLANTS	With +1°C: -0.8% nuclear power output. -0.6% coal/gas power output U.S.: -1% reduction in electricity generation means a drop in supply of 25 billion kWh	(Mideksa and Kallbekken, 2010)
TRANSMISSION	California power grid. -7-8% transmission line capacity and -2-4% substation capacity due to +5°C (2100)	(U.S. Department of Energy, 2013)

In this section we analyze the impacts of temperature changes in the energy supply and precisely the alteration of the efficiency of the supply facilities due to the increase of air temperature. The raise of air temperature principally affects the efficiency of solar panels, the thermal power plants and the infrastructures used for the transmission and the distribution of power, and transfer of oil, gas and other fuels.

Solar panels

Climate change can affect the performance of a solar cell in two main ways. Firstly, the current delivered by a solar cell is very dependent on the irradiance of the incoming sunlight. And secondly, solar cells are very sensitive to any changes in temperature. These changes can either be caused by alterations in the irradiance or in the amount of wind cooling the solar panel, but especially by alterations in the overall ambient temperature. The increase of air temperature can modify the efficiency of photovoltaic cells and ultimately reduce the PV electric generation.

Thermal power plants

Lots of different effects of global climate change may affect the electricity production in a thermal based power plant. The principally effects are the increase of temperature and the changes in water characteristics. Then the technologies that could be affected are coal, natural gas, nuclear, geothermal and biomass residues power plants. All these plants have in common the power cycle for the energy production: it could be the Rankine and the Brayton-Joule cycle. These infrastructures need a heating and a cooling system to generate electricity, and these structures are the most affected systems of the power cycle and consequently of the power plant. The average ambient conditions like temperature, pressure, humidity and water availability influence the cycles and thus the supply of energy.

The ambient conditions which mostly affect the energy production are temperature and water availability. Following there will be some indications about the two types of power cycle and their impacts. Then there will be an account of the impacts, with trends and data, caused only by temperature changes and not water availability changes: this specific description will be exposed in the next paragraph which concerns the refrigeration impacts on power supply.

- *Brayton-Joule cycles*. There are different types of Brayton-Joule cycles, like the open, combined and IGCC (Integrated Gasification Combined Cycle). The power output and the efficiency of the turbine may be affected by variations in ambient temperature and humidity. A rise in temperature raises the air specific volume, increasing the consumption of energy in the compressor and hence reducing the amount of net energy generated in the cycle. This modification induces a decrease in electricity generation or higher fuel consumption. Furthermore, the temperature and availability of water affect a portion of the Combined Cycle, and precisely the steam part. The next point, related to the Rankine cycle, displays better the theme.
- *Rankine cycle*. Different power plants use this kind of power cycle to generate electricity, as coal, oil, nuclear, geothermal, biomass residues and IGCC. They all have in common the need of cooling, which could be affected by air temperature modifications and especially water alterations. A steam cycle requires lot of water:

> each kWh of generated electricity requires around 100 liters of water, calculated by averaging all existing different cooling systems (Wilbanks et al., 2008, in Schaeffer et al., 2012, p. 6). Projected changes in water availability make that power plants will increasingly compete with other water users like agriculture and public supply, especially in water-stressed areas. Alterations in quantity and quality of water suggest that closed-circuit cooling systems are less vulnerable than once-through systems. An increase in water temperature can affect the cooling efficiency of the generation cycle and increase water demand.

All the climate change's consequences, which could impact the thermal power supply, are quite small, but they could add up to a significant loss in power generation in a specific region that relies on thermal power plants.

In the paper *The impacts of climate change on the electricity market: a review* (Mideksa and Kallbekken, 2010) the authors reported the results of two different studies (*The impact of climate change on thermal power supply,* 2009, Linnerud et al.; *Effects of climate change on energy production and use in the United States,* 2007, U.S. Climate Change Science Program and the Subcommittee on Global change Research) which analyzed the correlation between air temperature and power output. The first concluded that for a temperature increase of 1°C nuclear power output decreases by 0.8% and coal and gas power output decreases by 0.6%, due to thermal efficiency loss. The second reported, in the case of USA, that a 1% reduction in electricity generation due to increases temperatures would amount to a drop in supply of 25 billion kWh. This data highlights that even if the efficiency loss is small in percentage terms, the overall effects of relatively small changes in efficiency could still be substantial, as the change applies to the major share of power production.

Transmission, distribution and transfer

The transmission and distribution of electricity through power lines are subject to climate variability and the efficiency of the transmission and distribution depends on various factors, including the temperature of surrounding environment.

Mideksa and Kallbekken in their paper (Mideksa and Kallbekken, 2010) cited the study *The future of European electricity: choices before 2020* (2008) of Eskeland et al., in which the authors report that there could be an electricity loss in transmission due to higher temperature and the resistance it induces on power lines.

In the report *U.S. energy sector vulnerabilities to climate change and extreme events* (U.S. Department of Energy, 2013) the authors gave an account of the impacts of temperature on the electric grid. They concluded that climate change projections like increasing air temperatures, more frequent and severe wildfires and increasing intensity of storm events, could implicate a reduction in transmission efficiency and available transmission capacity, and an increased risk of physical damage. They reported the results of a study on the California power grid which projected that during the hot periods of August in 2100, under a higher emissions scenario, a 9°F (5°C) increase in air temperature could decrease transmission line capacity by 7–8%. The same study projected that 9°F (5°C) warming in 2100 could cause substation capacity to fall by 2–4% (U.S. Department of Energy, 2013, p. 12).

3.2.4.2 Impacts of water changes on energy supply

Table 3.14 Projected impacts of water changes on energy supply's refrigeration

IMPACT	PROJECTIONS	REFERENCE
REFRIGERATION	-0.45% power output due to +1°C	(Mideksa and Kallbekken, 2010)
	Between 2010 and 2035: water withdrawals: +20%; water consumption: +85%	(IEA, 2012)

As for temperature, this part of the thesis does not analyze in general the energy supply alterations, due to water system changes to climate change, but it concentrates on a specific problem: the refrigeration of energy supply facilities.

In the previous section we talked about the different kind of power cycles, used to generate electricity in the supply plants. We highlighted that the Rankine cycle relies very much on water and that an increase in water temperature can affect the cooling efficiency of the generation cycle and increase water demand. This sentence is supported by the results obtain by two different researches.

In *The impacts of climate change on the electricity market: a review* (Mideksa and Kallbekken, 2010) is reported the data of the research of Durmayaz and Sogut, 2006, *Influence of cooling water temperature on the efficiency of a pressurized-water reactor nuclear-power plant.* The authors investigated the impact of changes in cooling water temperature on the thermal efficiency of nuclear power plants using plant level data and an engineering model. Their result suggests that a 1°C increase in the temperature of the environment reduces power output by approximately 0.45% points.

The water demand for thermoelectric generation then was investigated in chapter 17 *Water for energy: is energy becoming a thirstier resource?* of *World energy outlook 2012* (IEA, 2012). In the New Policies Scenario (IEA scenario) withdrawals will increase by about 20% between 2010 and 2035, but consumption will rise by a more dramatic 85%. These trends are driven by a shift towards higher efficiency power plants with more advanced cooling systems (that reduce withdrawals but increase consumption per unit of electricity produced).

3.2.4.3 Impacts of extreme events on energy supply

Table 3.15 Projected impacts of extreme events on energy supply

IMPACT	PROJECTIONS	REFERENCE
HYDROPOWER	Affected by flooding. Shutting down of the turbine operation or (rare) destruction of power plants and/or dams	-
WIND POWER	Stressed by extreme wind speeds (25m/s): the strain on the turbine will be too high, and it could provoke serious damages	-
BIOFUELS	Reduction of productivity of the crops by droughts, frosts, extreme temperatures and precipitations Destruction of biofuels' production equipment by storms/cyclones	-
THERMAL PLANTS	Inland reactors/plants. Subject to heat waves (reduction of power generation) and inland floods (damage of ancillary facilities) Coastal reactors/plants. Subject to the rise of sea level (inundation, erosion), instability of shorelines, storms, flooding	(Kopytko and Perkins, 2011)
FOSSIL FUELS	Increase of production shutdowns to avoid life of environmental damage	(Burkett, 2011)
TRANSMISSION	Disruption of infrastructure of the electricity grid by weather phenomena and permafrost thawing	-
TRANSFER	Interruption of barge transport of crude oil, petroleum products and coal due to decreased water levels (droughts)	(U.S. Department of Energy, 2013)

Note. (-) means that there is no a specific document which refers to

The term extreme event is used to refer to all the weather and climate events, which manifest a greater severity than common weather and climate events. The episodes we are referring to are heat waves, heavy precipitation, cyclones, hurricanes and extreme sea level events.

The severe episodes can have a debilitating impact on energy supply and more specifically they contribute to the reduction of energy generation and even the interruption. They affect all energy supply facilities, from the hydropower plants to the wind turbines, from biofuels productivity to thermal and nuclear plants, from oil and gas production to electricity grid and transfer of fuels.

Normally the extreme event which affects hydropower generation is flooding. Hydropower plants are able to withstand flooding events by opening floodgates and shutting down turbine operation. But in rare cases hydropower plants and/or dams can be destroyed by flood events.

Wind power generation could be stressed principally by two different events. Windmills can today only operate up to extreme wind speeds of around 25m/s. At higher wind speeds the strain on the turbine would be too high, which could provoke serious damages. In case of extreme winds presence, the electricity production will be shut down. The production could be also hampered by atmospheric icing: the efficiency gets lower when wind power is produced in icing conditions. Global warming facilitates the melting of ice, raising the performance of wind turbines in those areas characterized by icing problems. But extreme precipitations associated with low temperatures could still cause ice formation in north latitudes, reducing the performance of wind turbines and even the interruption.

Biofuels productivity could vary owing to modifications in climate, in atmospheric concentration of CO_2 and presence of extreme events. Droughts and frosts, extreme temperatures and precipitations and hurricanes reduce the productivity of the crops and decrease biomass availability. Storms and cyclones could also destroy the equipment for biofuels production.

The impacts caused by extreme events to thermal and nuclear power plants were largely studied by researchers to prevent possible significant damages to these facilities, which are essential for the supply of electricity to industries and population. Serious accidents to thermal and nuclear power plants should be avoided to not create disasters for the environment and population, because the fuels used and the processes are heavily pollutants. Kopytko and Perkins in *Climate change, nuclear power, and the adaptation-mitigation dilemma* (Kopytko and Perkins, 2011) concentrated on the adaptation-mitigation dilemma of the nuclear power plants, analyzing the safety and the interruption problems of these structures related to climate change. Most of the impact they analyzed could be referred to other types of power plants, like coal, oil, gas, solar and biomass plants: basically the analyzed impacts could be referred to all those plants which use a thermal cycle to generate electricity. The authors focused their attention on inland and coastal nuclear power plants, located respectively in France (where the 75% of electricity is generated by nuclear plants using 44 reactors) and in USA (104 reactors, 15 of which are located within 2 miles of the coast). The International Atomic Energy Agency (IAEA) created guidelines on adapting nuclear power plant design and operation to climate change. The authors studied the nuclear sites considering the major hazards elaborated by IAEA, which are the temperature of air and sea, the patterns, frequency and strength of winds, the characteristic of precipitation, the flow rates of rivers and rises and anomalies of sea levels. Inland reactors are subject to heat waves, which reduce the power generation and inland floods, which could damage ancillary facilities and put a risk on the stability of the plants. Coastal reactors instead are subject to the rise of sea level, which can inundate the reactor sites and increase erosion and instability of shorelines. These reactors are also exposed to intense storms combined with sea level rise, which can produce more severe episodes of flooding and wind damage.

Oil and gas operation in low-lying coastal areas, onshore facilities and offshore facilities could be affected by climate change. The paper *Global climate change implications for coastal and offshore oil and gas development* (Burkett, 2011) indicated six key climate change drivers for coastal and offshore oil and gas development: sea level rise, storm intensity, wave regime, air and water temperature, precipitation patterns, changes in CO_2 and ocean acidity. Oil and gas supply from offshore and coastal low-lying facilities can be disrupted by extreme weather events, such as intense hurricanes, that could lead to production shutdown to avoid life or environmental damages. An expected increase in frequency, duration and intensity of such extreme events can have significant impacts on oil and gas supply. The supply may also be affected by structural damages caused by other extreme events, like flooding from sea level rise and storm surges, that may lead to erosion and other damages. Also oil refining may be affected by extreme events like lower water availability induced by climate change: oil refining is vulnerable to water availability because it is a large water consumption activity. The water demand in oil refineries can be impacted by higher temperatures, as most of water is used in cooling units. Then, the gas and oil transmission systems could be affected by factors as mud flows, floods, landslides and other extreme meteorological events. Storm surge and high winds historically have not had much impact on pipelines – either onshore transmission lines or offshore pipelines – because they are buried underground. However, offshore pipelines could be damaged by hurricanes.

Extreme weather events could affect the delivery of electricity through disruption of infrastructure of the electricity grid. The weather phenomena could be extreme winds and ice load, lighting strikes, avalanches, landslides and flooding. In particular, excessive icing overhead lines can cause other outages, resulting in higher repair costs. Temperature extremes lead to electricity loss in transmission. Further, the permafrost thawing is considered a risk: much of the existing infrastructure erected in northern regions is located in areas of high hazard potential and could be affected by thaw subsidence.

Even the transfer of energy fuels by train or by barge will suffer extreme events phenomena. In *U.S. energy sector vulnerabilities to climate change and extreme* events (U.S. Department of Energy, 2013) the authors illustrated that a decreased water levels in rivers and ports and increasing intensity and frequency of flooding, could cause interruptions and delays in barge and other fuel delivery transportation routes, resulting in delivery delays and increased costs.

3.2.4.4 Impacts of energy resource changes on energy supply

Table 3.16 Projected impacts of energy resource changes on energy supply

IMPACT	PROJECTIONS	REFERENCE
HYDROPOWER	U.S. Colorado River: -40% hydropower production by the middle of 21st century U.S. Central Valley: -10-12% hydropower production	(Mideksa and Kallbekken, 2010)
	+0.08% of total generation, +2.46 TWh from current generation, reaching 2931 TWh (2050)	(Hamududu and Killingtveit, 2012)
WIND	Offshore wind farms around the North Sea: +3-9% due to increases in wind speeds	(Mideksa and Kallbekken, 2010)

IMPACT	PROJECTIONS	REFERENCE
WIND	Continental U.S.:-30-40% of wind power generation due to -10-15% mean wind speeds	(Breslow and Sailor, 2002)
BIOFUEL	The magnitude of energy generating from biofuels depends on the quantity of energy resource produced	-
SOLAR	Projections: 2071-2100. Reference period: 1980-2000 -6% electricity output due to -2% solar radiation (2071-2100)	(Fidje and Martinsen, 2006)

Note. (-) means that there is no a specific document which refers to

The supply of electricity from renewable resources strongly depends on the availability of the resources themselves. In the future the supply of energy from renewable energy will become increasingly essential due to the fact that non-renewable sources are using up and that the energy system is evolving to be renewable-dependent to meet the mitigation and environmental clean-up targets. For these reasons it is essential investigate on the changes in energy supply due to changes in energy resources.

Differently from section 3.2.2, the focus of this part of the thesis is the assessment of the changes in energy production due to the changes of resource availability. While the outcomes of section 3.2.2 are the changes in the amount of energy resources, the conclusions of this part are the changes in the amount of energy produced.

Hydropower generation

The hydropower generation is one of the supply's methods on which we have to base future energy production. The amount of electricity that can be generated from hydropower plants depends on the installed generation capacity and especially on the variation in water inflows to the plant's reservoirs. Natural climate variability already has great influence on the planning and operations of hydropower systems. Changing climate conditions may affect the operation of the existing hydropower system and even compromise the viability of new entrepreneurships. In fact, global climate change can add a significant amount of uncertainty to the already uncertain operation of hydropower systems.

The California Climate Change Center in its paper *Climate change impacts on high-elevation hydropower generation in California's Sierra Nevada: a case study in the upper American river* (California Climate Change Center, 2006) reported as results that all scenarios show similar pattern of generation, with maximum generation during the summer months and minimum during spring and winter. In addition they added another interesting finding, that the change in timing of inflows will have a smaller than expected negative impact on hydropower generation in that system.

In *The impact of climate change on the electricity market: a review* (Mideksa and Kallbekken, 2010) the authors reported several results of other investigations on hydropower generation supply.

- Barnett et al., *The effects of climate change on water resources in the West: introduction and overview*, 2004. The hydropower production based on the Colorado River could decrease by as much as 40% by the middle of the 21st century.
- Van Rheene et al., *Evaluating potential climate change impacts on water resources systems operations: case studies of Portland, Oregon and Central Valley, California*, 2003. Hydropower in the Central Valley could decrease between 8% and 11% in Lake Shasta and between 10% and 12% for the Central Valley as a whole.
- Bye, *The electricity market and climate change – or vice versa*, 2008. The author analyzed the effect of climate change on supply based on hydro and wind power in Northern Europe. He reported that the supply of power would raise by 1.8% in 2040 relative to 2001. He pointed also up that climate change could affect hydropower production through dam safety. Most current dams are built without taking into account the possible impact of climate change and may have lower reservoir capacity to handle frequent extreme events associated with river flow and snow melt. About dams, if the changes take place slowly over time, the dam safety issue becomes relatively less important as new dams compatible with the new climate can be built while the old dams are taken out of use partly due to the redistribution of water flow and temperature and partly due to depreciation.

Then in *Assessing climate change impacts on global hydropower* (Hamududu and Killingtveit, 2012) the authors aimed to evaluate the changes in global hydropower generation resulting from predicted changes in climate. The study used an ensemble of simulations of regional patterns of changes in runoff, computed from global circulation models (GCM) simulations with 12 different models. The results indicated that there would be large variations of changes (increases/decreases) in hydropower generation across regions and even within regions. Globally hydropower generation is predicted to change very little by the year 2050 for the hydropower system in operation today. There are many regions where runoff and hydropower generation will increase due to increasing precipitation, but also many regions where there will be a decrease. Even if individual countries and regions may experience significant impacts, climate change will not lead to significant changes in the global hydropower generation, at least for the existing hydropower system. In Africa, there are some countries with increasing hydropower generation and others with decreasing hydropower generation. For Asia, positive trends owing to climate change have been projected for most countries. An exception will be the Middle East which has decreasing trends. The Americas will have a continental net increase with major producers having increases (south and north) and only Central America having a reduced generation in the future. Southern, Eastern and Western Europe will have reductions while Northern part will have increases. As the large producers are in the Northern region, the continental changes will be positive in hydropower generation. Summing up, the global change in future hydropower generation due to climate change will show a slight increase over the current global hydropower generation of 2.46 TWh, reaching 2931 TWh. The percentage change of total generation will be of 0.08%.

The other factor which affects the hydropower generation is the Glacial Lake Outburst Flooding (GLOF). The impact of future GLOFs on hydropower will be proportional to the amount of water in the lake, slope of its path downstream and proximity of the hydropower plant. GLOF would cause both vertical and lateral erosion (Agrawala et al., 2003, p. 31).

Wind generation

The magnitude of electricity we can generate from wind power generation depends on the energy content of wind. An important property of the energy content is that it increases with wind speed to the third power. A wind speed of 3 m/s can produce 16 W/m^2 of wind power whereas a wind speed of 12 m/s can produce 1305 W/m^2 wind power. Thus, relatively small changes to the wind speed can have very large effects on wind power generation. Another important climatic parameter for the supply of energy is the frequency of extreme wind speeds.

In the article *The impact of climate change on the electricity market: a review* (Mideksa and Kallbekken, 2010) the authors cited the 2006 study of Sood and Durance *The influence of the North Atlantic Oscillation on the wind conditions over the North Sea* which investigated the wind potential over the North Sea. The wind power from offshore wind farms is likely to increase by 3 to 9% around the North Sea due to increases in wind speed under a business as usual scenario.

Breslow and Sailor in *Vulnerability of wind power resources to climate change in the continental United states* (Breslow and Sailor, 2002) calculated the wind power generation considering the results of wind speed changes of two climatic models, the Hadley and the CCC model. The Hadley model suggested minimal climate change impact, while the Canadian (CCC) suggested reductions in mean wind speeds on the order of 10-15%. Considering that wind power generation is a function of the cube of the wind speed, these decreases in wind speed correspond to potential reductions in wind power generation on the order of 30 to 40%. Anyway, there is not so much literature that treats the changes of energy supply from wind power generation. The researches concentrate more on the evaluation of the changes in wind patterns, because is simply to find the correlated changes in wind power generation.

Biofuel generation

Vulnerability of liquid biofuels production can relate to impacts on crop yield caused by modifications in climate and the atmospheric concentration of CO_2. These modifications include regional temperature, precipitation and frequency of extreme events, like droughts and frosts. Lower availability of water, caused by increase evapotranspiration due to rising temperatures and lower precipitation levels, can reduce crop productivity. High CO_2 levels, up to a saturation limit, increase the photosynthetic rate, leading to higher productivity. This effect can be offset by an increase in temperature, since higher temperatures reduces photosynthetic activity.

However, there is no literature about changes in energy supply of biofuels, because the magnitude of energy generating from biofuels depends on the quantity of energy resource produced. As for wind energy, the studies on the expected availability of future energy resource, give us future projections of energy supply caused by climate change. The available researches in literature do not analyze the impacts on biofuels production infrastructure, but only analyze the impacts on crop production for generating the biofuel energy resource.

Solar power

Solar energy generation is especially affected by increasing temperatures, which modify the efficiency of photovoltaic cells. Also a change in global radiation alters the electricity output of solar panels. Two researchers, Fidje and Martinsen, studied the effects on solar radiation modifications on solar panels in *Effects of climate change on the utilization of solar cells in the Nordic region* (Fidje and Martinsen, 2006). The authors experimented in Oslo how much a reduction in solar radiation could affect a PV generation. They verified that when the global solar radiation is reduced by 2%, the electricity output of solar cells would be reduced by about 6%. These results were calculated using the A2 and B2 IPCC scenarios for the period 2071-2100. To know this information is fundamental, because these two scenarios represent a decrease in global solar radiation and an increase in temperature. Thus, the results are affected by solar radiation but also by temperature.

3.2.4.5 Impacts of climate change mitigation on energy supply

Table 3.17 Projected impacts of climate change mitigation on energy supply

IMPACT	PROJECTIONS	REFERENCE
MITIGATION	-40-70% GHG emission in 2050 than 2010 to reach 450 ppm CO2eq by 2100 (+2°C relative to preindustrial level) -25-55% GHG emission in 2050 than 2010 to reach 500 ppm CO2eq by 2100 -5-45% GHG emission in 2050 than 2010 to reach 550 ppm CO2eq by 2100 To reach 450 ppm CO_2eq by 2100: improvements in efficiency, tripling/quadrupling share of zero carbon energy supply by 2050	(IPCC, 2015)

As already stated, this specific paragraph does not focus on those changing parameters which all together affect energy supply. The attention here is concentrated on the mitigation aspect in the impacts analysis.

Adaptation and mitigation are two different used techniques to contrast climate change in the energy sector. The conventional view is that adaptation and mitigation are incompatible, but in the reality one does not exclude the other. These two methods can work together optimally and give benefits one to the other.

The effects of mitigation strategies on the energy supply sector are very simple to note. Mitigation is a human intervention act to reduce the concentration of greenhouse gases in the atmosphere, reducing the generation of these or creating specific sinks where we can store them. The impacts of mitigation on the energy supply system are simple: to reduce the electricity generation using fossil fuel plants and to increase the production with no-CO_2 generation facilities. It is necessary implement a new energy supply system: the target is to convert the system from a fossil fuel base to a renewable energy base.

Some objectives were set at global, regional or national level. The European Union approved in 2009 the so-called “20-20-20 Targets” in the Directive 2009/29/CE. The objectives were to reduce the emission of greenhouse gases of the 20% in 2020 relative to the 1990 level, to generate the 20% of the energy requirements with renewable sources and to increase the energy efficiency of a 20%. The European Council then approved on 24th October 2014 the *EUCO 169/14* (European Council, 2014) in which it endorsed a binding EU target of an at least 40% domestic reduction in greenhouse gas emissions by 2030 compared to 1990.

The Working Group III of the IPCC studied for the AR5 the future emissions from the energy supply sector, finding that are projected to almost double or even triple by 2050 to the level of 2010 unless energy intensity improvements can be significantly accelerated beyond historical development. Decarbonizing electricity generation is a key component of cost-effective mitigation strategies in achieving low-stabilization levels. So the WGIII in *Climate change 2014: mitigation of climate change* (Intergovernmental Panel on Climate Change et al., 2015) highlighted that GHG emissions from energy supply can be reduced significantly by replacing current world average coal-fired power plants with modern, highly efficient natural gas combined-cycle power plants or combined heat and power plants, only as bridge technology.

There are multiple scenarios with a range of technological and behavioral options, with different characteristics and implications for sustainable development, that are consistent with different levels of mitigation. For the AR5 about 900 mitigation scenarios have been collected in a database. This range spans atmospheric concentration levels in 2100 from 430 ppm CO_2eq to above 720 ppm CO_2eq, which is comparable to the 210 forcing levels between RCP 2.6 and RCP 6.0. Mitigation scenarios in which it is likely that the temperature change caused by anthropogenic GHG emissions can be kept to less than 2 °C relative to pre-industrial levels are characterized by atmospheric concentrations in 2100 of about 450 ppm CO2eq. Mitigation scenarios reaching concentration levels of about 500 ppm CO_2eq by 2100 will limit the temperature change to less than 2°C relative to pre-industrial levels. Scenarios that exceed about 650 ppm CO_2eq by 2100 are unlikely to limit temperature change to below 2°C relative to pre-industrial levels. Scenarios reaching atmospheric concentration levels of about 450 ppm CO_2eq by 2100 (consistent with a likely chance to keep temperature change below 2 °C relative to pre-industrial levels) include substantial cuts in anthropogenic GHG emissions by mid-century through large-scale changes in energy systems and potentially land use. Scenarios reaching these concentrations by 2100 are characterized by lower global GHG emissions in 2050 than in 2010, 40% to 70% lower globally, and emissions levels near zero GtCO_2eq or below in 2100. In scenarios reaching about 500 ppm CO_2eq by 2100, 2050 emissions levels are 25% to 55% lower than in 2010 globally. In scenarios reaching about 550 ppm CO_2eq are from 5% above 2010 levels to 45% below 2010 levels globally. At the global level, scenarios reaching about 450 ppm CO_2eq are also characterized by more rapid improvements in energy efficiency and a tripling to nearly a quadrupling of the share of zero- and low- carbon energy supply from renewables, nuclear energy and fossil energy with carbon dioxide capture and storage (CCS), or bioenergy with CCS (BECCS) by the year 2050. These scenarios describe a wide range of changes in land use, reflecting different assumptions about the scale of bioenergy production, afforestation, and reduced deforestation. All of these emissions, energy and land-use changes vary across regions.

PART B

VULNERABILITIES OF ENERGY SYSTEMS TO CLIMATE CHANGE

CHAPTER 4

ENERGY SYSTEMS VULNERABILITIES

Once having talked about the impacts of climate change on natural and energy systems, the purpose of this work is to recognize the vulnerabilities of energy systems due to climate change, in order to find the best way to adapt them. We can say that the investigation partially follows the title of the Working Group II contribution to the Fifth Assessment Report of the IPCC: *Climate change 2014: Impacts, Adaptation, and Vulnerability* (IPCC, 2014). In Part A we firstly analyzed the impacts of climate change to energy system. In Part B we are going to assess the vulnerabilities of the system related to climate change. Finally, in Part C, we will investigate the possible measures to adapt the system to climate change.

This section is essential for the adaptation analysis. It shows the components of energy systems which are vulnerable to climate change and require specific interventions to form a resilient and adapted energy system to the changes. The analysis will start defining the concept of vulnerability: this notion will be useful to evaluate the vulnerabilities of energy systems to climate change. The chapter will conclude focusing on metrics and their necessity. A set of parameters and indicators (metrics) to measure the vulnerability and resilience of an energy system has a remarkable importance, because it helps to identify policies, strategies and appropriate measures to reduce vulnerabilities, and realize an adapted energy system to climate change.

4.1 Vulnerability definition

Vulnerability is a central concept in climate change research. This crucial notion has a significant importance also in other contexts. A large number of research communities, such as those dealing with disaster management, public health, development and secure livelihoods, gives great relevance to vulnerability like climate impact and adaptation. For this specific reason – that vulnerability has a key role in many research contexts and not only in the energy one – the different research communities conceptualize its personal definition of vulnerability in very different ways.

It does not exist a unique definition of vulnerability of *energy* system to climate change: precisely, it does not exist at all. In literature could be found the definition of vulnerability of a *generic* system to climate change, like the HELIO International one in *Climate-proofing energy systems* (Williamson et al., 2009, p.53):

> Vulnerability is the degree to which a system or unit (such as a human group or a place) is likely to experience harm due to exposure to risk, hazards, shocks or stresses.

Füssel in its article *Vulnerability in climate change research: a comprehensive conceptual framework* (Füssel, 2005) notes the widespread disagreement about the appropriate definition of vulnerability, which frequently causes misunderstanding in interdisciplinary research on vulnerability and adaptation to climate change. His purpose is to attempt to ameliorate the confusion on vulnerability's definition, by presenting a comprehensive and consistent conceptual framework of vulnerability. This framework should level out the terminology of vulnerability, to support interdisciplinary global change research.

Of course, the IPCC drew up a definition of vulnerability related to climate change. Most researches refer to this specific definition: this thesis too will allude to it. However, to better understand the various facets of this precise definition, the conceptual framework of vulnerability, composed by Füssel in its above mentioned paper, will be reported.

4.1.1 The IPCC definition of vulnerability

The Intergovernmental Panel on Climate Change, basing on the UNFCCC guidelines, defines vulnerability as:

> The degree to which a system is susceptible to, and unable to cope with, adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude, and rate of climate change variation to which a system is exposed, its sensitivity, and its adaptive capacity (Parry and Intergovernmental Panel on Climate Change, 2007, p. 883)

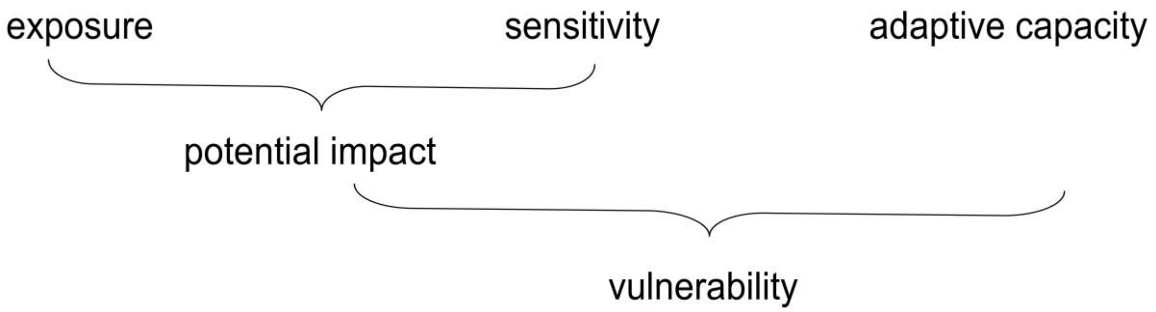

Figure 4.1 Graphic definition of vulnerability (Dagma Schröter and ATEAM consortium, 2004)

This definition is set up on certain correlations between a system and climate change. The diagram of Figure 4.1 could sum up these correlations.

Vulnerability, according to the IPCC definition, is an integrated measure of the expected magnitude of adverse effects to a system, caused by a given level of certain external stressors. Vulnerability includes an external dimension, which is represented by the *exposure* of a system to climate variations, as well as an internal dimension, which includes its *sensitivity* and its *adaptive capacity* to these stressors. At this point it is necessary to report the meanings of the key terms that form the IPCC definition of vulnerability, as done also by Füssel and Kleine in *Climate change vulnerability assessments: an evolution of conceptual thinking* (Füssel and Klein, 2006).

> **Exposure:** The nature and degree to which a system is exposed to significant climatic variations.
>
> **Sensitivity:** The degree to which a system is affected, either adversely or beneficially, by climate variability or change. The effects may be direct (e.g. a change in crop yield in response to a change in the mean, range or variability of temperature) or indirect (e.g., damages caused by an increase in the frequency of coastal flooding due to sea level rise).
>
> **Adaptive capacity:** The ability of a system to adjust to climate change (including climate variability and extremes), to moderate potential damages, to take advantage of opportunities, or to cope with the consequences.

The exposure of a system to climate stimuli depends on the level of global climate change and, due to the spatial heterogeneity of anthropogenic climate change, on the system's location. The sensitivity of a system denotes the response relationship between its exposure to climate stimuli and the resulting impact. The adaptive capacity of a system or society describes its ability to modify its characteristics or behavior in order to cope better with changes in external conditions. In *Resilience, vulnerability, and adaptive capacity: implications for system performance* (Dalziell and McManus, 2004) the authors defined adaptive capacity as *'the extent to which a system can modify its circumstances to move to a less vulnerable condition'*. They clarified that adaptive capacity reflects the ability of the system to respond to changes in its external environment and to recover from damage to internal structures within the system, that affect its ability to achieve its purpose.

The ensemble of these systems' aspects and climate change determines the definition of vulnerability. Vulnerability to climate change, as conceptualized by the IPCC, is a broader concept than potential impacts of climate change, as determined in climate impact assessment. Vulnerability assessments tend to include additional factors that increase their relevance for decision-makers. This is achieved by a more comprehensive representation of the main stressors affecting a system, including non-climatic stressors, and consideration of the socio-economic factors, that determine the differential potential of communities to adapt to changing conditions. We must also remember, according to Dalziell and McManus, that when we analyze vulnerability we must be aware that not everyone suffers the same way in response to the same event.

Impacts of climate change and vulnerability have a particular correlation. The potential impacts of climate change on a particular system (together with its adaptive capacity) determine the vulnerability of that system to climate change. However, it does not suggest that impacts cause vulnerability. This is a crucial point of the vulnerability analysis, which always must be taken into account.

The IPCC definition of vulnerability of a system to climate change is largely disputed by several researchers. Füssel in *Vulnerability in climate change: a comprehensive conceptual framework* (Füssel, 2005) presented a conceptual framework able to reconcile the large variety of vulnerability concepts found in literature, in order to resolve the misunderstanding between some scientists and the IPCC with its vulnerability definition.

4.1.2 The conceptual framework of vulnerability

Vulnerability describes a central concept in a variety of research contexts. It has its roots in geography and natural hazards, but is now used by various research communities. However, scientific communities conceptualize vulnerability in very different ways.

The existence of competing conceptualizations and terminologies of vulnerability has become particularly problematic in the context of anthropogenic climate change. The cross-cutting nature of the global climate problem requires the intense collaboration of scientists from different research traditions, such as climate science, disaster management, risk assessment, development, economics and policy analysis. This collaboration must be based on a consistent terminology that facilitates researchers from different traditions to communicate clearly and transparently, despite differences in the conceptual models applied.

The paper to which we refer, *Vulnerability in climate change: a comprehensive conceptual framework* (Füssel, 2005), assumes that there is no single correct or best conceptualization of vulnerability: it suggests the need of a consistent framework and terminology for interdisciplinary global change research. The framework consists of three components.

1. Terminology of vulnerable *situations*. It describes the context of a vulnerability assessment in terms of the vulnerable system, the hazard of concern, the valued attributes of that system that are threatened by its exposure to the hazard, a temporal reference.
2. Classification scheme of vulnerability *factors*. The classification takes into account two independent dimensions: scale and disciplinary domain.
3. Terminology of vulnerability *concepts*. This terminology describes any conceivable conceptualization of vulnerability based on the groups of vulnerability factors it includes.

Situations

Scanning the literature, we could note that all the frameworks of vulnerability specify four fundamental dimensions to describe the context of a vulnerable assessment.

1. *System.* The system, region, population group and/or sector of concern.
2. *Hazard.* The external stressor (or set of stressors) of concern. The United Nations in *Living with risk: a global of disaster reduction initiatives* (United Nations, 2004, cited in Füssel, 2005) defines a “hazard” as “a potentially damaging physical event, phenomenon or human activity that may cause the loss of life or injury, property damage, social and economic disruption or environmental degradation”. Hence, a hazard is understood as some external influence that may adversely affect a valued attribute of a system.
3. *Valued attribute.* The valued attributes (or variables of concern) of the vulnerable system that are threatened by its exposure to the hazard. Complex hazards, such as anthropogenic climate change, may have a wide range of effects on a particular system or community.
4. *Temporal reference.* The time period of interest. If the vulnerability of a system or its exposure to the hazard is expected to change significantly during the time period considered in an assessment, statements about vulnerability should specify a temporal reference, i.e., the point in time or period of time that they refer to. This is particularly relevant for vulnerability assessments, addressing anthropogenic climate change, which may have a time horizon of several decades or longer.

These four attributes are universally applicable to a wide range of contexts and to different traditions of vulnerability research. We can condense the four dimensions in this phrase from

Vulnerability in climate change research: a comprehensive conceptual framework (Füssel, 2005, p.6), to describe a vulnerable situation:

Vulnerability of a system's valued attribute(s) to a hazard (in temporal reference)

An example of fully description of vulnerability based on this structure is "vulnerability of a particular ecosystem's net primary production to wild-fires in 2050".

Factors

A clear description of the vulnerable situation is an important first step for avoiding misunderstandings around vulnerability. However, there are different interpretations of the term *vulnerability*.

Basing on the Füssel article (Füssel, 2005) we distinguish different vulnerability concepts by the vulnerability factors considered. The term vulnerability factor is used in a rather extensive sense. The meaning may be confused with the ones of risk factor. In this case, we can associate the word factor with feature/characteristic.

In literature, various proposed frameworks are not comprehensive and they use terminologies that are incompatible with each other. Some authors distinguish an external and an internal side of vulnerability to environmental hazards, with different meanings associated to these two categories. Most use these terms to distinguish the external stressors that a system is exposed to, from the internal factors that determine the effects on the system. Others use them to distinguish external structural socioeconomic factors from internal agency-oriented factors. The United Nations distinguish four groups of vulnerability factors that are relevant in the context of disaster reduction: physical, economic, social and environmental. Several researchers then distinguish biophysical (or natural) vulnerability from social (or socioeconomic) vulnerability.

Each of the terminologies cited above provides an important distinction of the factors that may be relevant for assessing the vulnerability of a system to a specific hazard. However, these terminologies are clearly incompatible with each other. According to (Füssel, 2005), the main reason for this confusion is the failure to distinguish between two largely independent dimensions of vulnerability factors: scale and disciplinary domain.

1. Scale: internal vs. external.

   Internal vulnerability factors refer to characteristics of the vulnerable system or community itself. Vulnerability actors that can be controlled by the considered community are also considered internal. All other vulnerability factors are denoted as external.

2. Disciplinary domain: socioeconomic vs. biophysical.
   Socioeconomic vulnerability factors are those that relate to economic resources: the distribution of power, social institutions, cultural practices, and other characteristics of social groups typically investigated by the social sciences and the humanities. Biophysical vulnerability factors, in contrast, are related to system properties investigated by the physical sciences.

Table 4.1 illustrates the independence of these dimensions by providing examples for the four categories of vulnerability factors, implicitly defined by them.

Table 4.1 Classification of vulnerability factors according to scale and disciplinary domain (Füssel, 2005, p.9)

		DOMAIN	
		SOCIOECONOMIC	**BIOPHYSICAL**
SCALE	**INTERNAL**	RESPONSE CAPACITY e.g., household income, social networks, access to information	SENSITIVITY e.g., topography, environmental conditions, current climate
	EXTERNAL	EXTERNAL SOCIAL FACTORS e.g., national policies, international aid, economic globalization	EXPOSURE e.g., severe storms, earthquakes, sea-level change

The classification scheme for vulnerability factors presented in Table 4.1 constitutes the minimal structure for describing the multitude of vulnerability concepts from the literature.

Concepts

Different interpretations of vulnerability can be distinguished, depending on which of the four groups of factors the vulnerability is included.

Vulnerability definitions which involve only *one* group of factors are denoted by adding the scale and the domain as qualifiers (or attribute: e.g. internal socioeconomic vulnerability). All relevant vulnerability definitions that include factors from *two* groups, combine factors from either the same scale or the same domain. The qualifier *cross-scale* is used for combinations of internal and external factors and *integrated* for combination of socioeconomic and biophysical factors. These attributes allow to uniquely denoting vulnerability definitions combining two groups of factors (e.g. cross-scale socioeconomic vulnerability) or all four groups (cross-scale integrated vulnerability).

The described terminology of vulnerability concepts has one limitation: it is indifferent with respect to time. The response capacity of a community to climate change involves its coping capacity (i.e. its ability to cope with short-term weather variations) as well as its adaptive capacity (i.e. its ability to adapt to long-term climate change), which may be determined by different factors. Discussions about vulnerability concepts that do not refer to a particular vulnerable situation, may thus have to specify explicitly the temporal reference of the vulnerability concepts in addition to their domain and scale. Therefore, we can use the terms *current*, *future* and *long-term* for this purpose, depending on weather the vulnerability concept refers to the present, to the future, or to the present and the future, respectively.

The combination of the terminology of vulnerable situations and the terminology of vulnerability concepts presented here, represents a comprehensive conceptual framework of vulnerability, spanned by the following six dimensions:

1. Temporal reference: current vs. future vs. long-term
2. Scale. Internal vs. external vs. cross-scale
3. Disciplinary domain. Socioeconomic vs. biophysical vs. integrated
4. Vulnerable system
5. Valued attribute
6. Hazard

The conceptual framework of vulnerability here presented can be applied in various ways. First, it allows communicating clearly which interpretation of vulnerability is used in a specific assessment. Second, it facilitates the debate on how and why different vulnerability concepts differ from each other. Third, it provides a framework for reviewing existing terminologies of vulnerability.

4.1.3 Approaches to vulnerability research

The conceptual structure of vulnerability could be applied in several approaches to vulnerability research. We will focus on the classical ones.

There are three major frameworks for vulnerability research. The four groups of vulnerability factors previously distinguished are typically included in the respective conceptualization of vulnerability.

Risk-hazard framework

The risk-hazard framework is applied to assess the risks to certain valued elements (exposure units) that arise from their exposure to specific hazards.

The framework distinguishes two factors that determine the risk to a particular system: the *hazard,* which is a potentially damaging physical event, phenomenon or human activity that is characterized by its location, intensity, frequency and probability, and the *vulnerability*, which denotes the relationship between the severity of hazard and the degree of damage caused. The risk-hazard approach is the most widely approach applied in technical literature on disasters. It generally assumes that hazard events are rare and that the hazard is known and stationary. Applying the previous terminology, this vulnerability concept is characterized as internal biophysical vulnerability. The terms *sensitivity* and *susceptibility* are also used to denote this concept.

Social constructivist framework

The social constructivist framework is applied to analyze who is most vulnerable, and why. According to this framework, vulnerability denotes the socioeconomic response capacity of individuals and groups to a variety of stressors.

The social constructivist framework, which is rooted primarily in political economy, prevails in poverty and development literature. Its vulnerability definition refers exclusively to people and it is based on an explanatory model of socioeconomic vulnerability to a range of stresses and consequences. This vulnerability concept is characterized as internal social vulnerability or cross-scale social vulnerability. The terms *response capacity* and *resilience* are also used to denote this concept.

Hazard-of-place framework

The two traditions (risk-hazard and social constructivist) have been combined in various integrated frameworks: the most notably of them is the hazard-of-place framework.

Integrated definitions of vulnerability are widely used in the context of global change and climate change, referring to regions, communities or other social units.

4.1.4 Vulnerability to climate change and the debated vulnerability definition by the IPCC

Anthropogenic climate change differs substantially from other concerns where vulnerability assessments have been applied, with important implications for the design of vulnerability assessments and the definition of key concepts.

Two main interpretations of vulnerability in climate change research have developed in response to the varied information needs of policymakers concerned to global climate change. To limit the adverse impacts of anthropogenic climate change, two fundamental options are considered: mitigation and adaptation. The two response options rely on information about the vulnerability of key systems to climate change. However, their specific information needs differ significantly, for instance, with regard to the relevant time horizon and the importance of distinguishing the impacts of anthropogenic climate change from those of natural climate variability.

The three main traditions of vulnerability research (risk-hazard, social constructivist and hazard-of-place) vary in their ability to provide information for the two response options (mitigation and adaptation). In principle, the risk-hazard framework can provide important information for mitigation policy but it needs to be substantially extended to reflect the specific characteristics of the hazard *global climate change*. The social constructivist framework can provide important information for the design of adaptation policies, in particular in developing countries. However, it also needs to be adapted to account for the unique challenges associated with long-term climate change.

Using the risk-hazard framework as starting point, we could develop a consistent definition of *future (or long-term) vulnerability to global climate change*, which we could then link to the contended vulnerability definition of the IPCC.

The risk-hazard framework has been widely applied in risk assessments to estimate the expected damages caused by different kinds of hazards, including climatic hazard. Standard applications of disaster risk assessment (DRA) are primarily concerned with short-term natural hazards, assuming known hazards and present vulnerability. Key characteristics of the climate change problem, in contrast, are: the long-term asset, that is global but not uniform, the involvement of multiple climatic hazards, the different effects on a system, the association with large uncertainties about future hazard levels and the attribution to human action. In summary, the hazard and risk events considered in DRA are limited in time and space, whereas the global climate change is not.

Thus, the conceptualization of *long-term vulnerability to global climate change* in opposition to Disaster Risk Assessment is discussed below.

1. **Climate change is continuous**
   DRA is concerned with discrete hazard events, which are the cause of risk to a system. Climate change in contrast is a continuous process that may either increase or decrease baseline risk level.
2. **Climate change is a long-term process attributable to human action**
   DRA sees climatic hazards as stationary and exogenous to the assessment, and assumes vulnerability to be constant. The long time scales of climate change, in contrast, require a dynamic assessment framework that accounts for uncertainty in future hazard levels and changes in all groups of vulnerability factors over time.
3. **Climate change is complex, global and spatially heterogeneous and uncertain**
   DRA assumes that the exposure of a vulnerable system to a hazard can be characterized by the description of the hazard at the spatial scale of the hazard. In vulnerability assessments to global climate change, however, the large deviation between the scales of the (global) hazard and the (regional) exposure units does not permit the implicit equation of *hazard* with *exposure to the hazard*. Two identical systems at different locations are likely to experience different exposures for the same magnitude of the hazard *global climate change* (e.g., expressed in terms of global

temperature change). Furthermore, the same amount of regional climate change (e.g., a given change in precipitation) may have very different impacts depending on the baseline climate.

4. **Climate change may have multiple effects on a system**
   DRA typically uses a single metric to describe the risk attributed to a specific hazard. Climate change, in contrast, typically has multiple incommensurable effects on societies and other vulnerable systems. For that reason, comprehensive characterizations of the vulnerability of a system to climate change generally require the use of multiple metrics.

The risks of future climate change to a system are determined by its future exposure to climatic hazards at the regional scale and by its future sensitivity to these hazards. Future exposure to regional climate hazards is determined by the future hazard level as well as by a regional exposure factor that describes the manifestation of climate change at the regional level. Future sensitivity to climate change depends on the current sensitivity of the vulnerable system as well as its adaptive capacity over time.

In summary, future risk is determined by future hazard level and three other factors: the regional exposure factor, current sensitivity and adaptive capacity. The three latter factors are exactly those considered in the vulnerability definition of IPCC. Hence, the IPCC definition of vulnerability consistently describes the *future (or long-term) vulnerability of any natural or social system to global climate change.*

4.1.5 Different views about vulnerability

As already said, vulnerability is not a straightforward concept and there is no consensus to its precise meaning. Some definitions of vulnerability are contradictory and the term is used to mean different things by different authors. There are many different definitions of vulnerability. Previously we chose one of them (the IPCC one) as the most suitable to describe the concept of vulnerability to climate change, delineating a conceptual framework to support it.

As reported by the Tyndall Centre in its *New indicators of vulnerability and adaptive capacity* (Adger et al., 2004), it is essential to stress that we can only talk meaningfully about the vulnerability of a specified system or exposure unit to a specified hazard or range of hazards. A system or exposure unit may be a region, population groups, community, ecosystem, country, economic sector, household, business or individual. The term hazard is used here to refer specifically to a physical manifestation of climatic variability or change, such as: drought, flood, storm, episode of heavy rainfall, a long-term change in the mean value of a climatic variable, a potential future shift in a climatic regime and so on. Climate hazards may be

defined in terms of absolute values or departures from the mean of variables as rainfall, temperature, wind speed, or water level, perhaps combined with factors such as speed, duration and spatial extent. Hazards are also referred to climate events. Crucially, hazards described here are purely physically defined.
However, we can say that the definitions of vulnerability in the climate change related literature tend to fall into two categories or views:

- In terms of the amount of (potential) damage caused to a system by a particular climate-related event or hazard;
- As a state that exist within a system before it encounters hazard events.

Focusing on this second point, the view of vulnerability as a state (i.e. as a variable describing the internal state of a system prior to the occurrence of a hazard event) has arisen from studies of the structural factors that make human societies and communities susceptible to damage from external hazards. In this formulation, vulnerability is something that exists within systems independently of external hazards.

We could give an example to explain better the concept. Imagine we have a box, which normally is filled to the half. This situation represents the normal operation of a system, which is not affected by climate change. The box presents also a little hole on one side in the upper half. This peculiarity exemplifies a vulnerability of the system. If we completely fill the box a leak occurs. The largest amount of water stands for a climate change, whereas the leak of water symbolizes the change of operation which the system undergoes. Without the appearance of a climate change event, we could not observe an alteration in the operation of the system, but the vulnerability would still be present.

In a subsequent section of the thesis we will display the vulnerabilities of the energy system related to climate change and not to any change in population, community, ecosystem, country, economy, household, business and individual. We will only focus on the vulnerabilities related to climate change, trying to incorporate all the vulnerabilities of the system, those ones that will appear or not in future due to climate change and.

4.1.6 The need of a metric for vulnerabilities

As we know the argument “climate change” holds a particular importance in the international concern. Mitigation and adaptation are considered the best approaches to deal with climate change. To be aware of the effectiveness of mitigation and adaptation measurements, the best approach is to evaluate the outcomes of the measurements. While a common metric in terms of “tons of CO_2 equivalent reduced” has traditionally been used in the mitigation context, there are no commonly accepted parameters and indicators to compare adaptation needs and the effectiveness of adaptation measurements. This lack could be explained by the fact that identification of adaptation measures is still in its infancy. Nevertheless, parameters and indicators (a metric) for energy system need to be developed and tested to assess whether proposed measures for adaptation are appropriate. Thus, the first step is to find the vulnerabilities of the system and elaborate a set of indicators to ponder them.

In order to understand better how to trigger and sustain positive synergies, the HELIO International developed a straightforward methodology and a set of indicators to assess the vulnerability and resilience of national level energy systems to climate change. Then by applying the indicators to energy systems, HELIO aimed to help identify policies and measures that can best facilitate and support adaptation activities. This procedure was descripted in the report *Climate-proofing energy system* (Williamson et al., 2009), which we use as base for the delineation of the metric for vulnerability.

4.2 The assessment of vulnerabilities

Climate vulnerability assessment normally is based on the vulnerability structure defined by the United Nations Framework Convention on Climate Change (UNFCCC), recalled by the IPCC and described in the first part of this chapter. The assessment describes vulnerability as the combination of three parameters: exposure, sensitivity and adaptive capacity (see also Figure 4.1). This method was used by several researchers and groups, like the World Bank in *Climate impacts on energy system. Key issues for energy sector adaptation* (Ebinger and World Bank, 2011) and ENDESA in its *La gestión del cambio climático: informe de adaptación* (Endesa, 2013). In the ENDESA's report it is clearly emphasized that there is the need of two types of data for assessing vulnerability: technical (type of technology and process) and climatic (current and future projections of climate change). The climate impacts, which are likely to affect the facilities (exposure), and the potential effects and consequences of the impacts (sensitivity) with the adaptive capacity, are the pillars of this kind of analysis.

The various documents, which we have considered, focus on different aspect of the energy system. For example, the ENDESA's report analyzed ENDESA's power plants (fossil fuels, nuclear, hydroelectric and wind) and distribution infrastructure. The World Bank took in consideration the entire energy system, concentrating on the supply of energy and the resource endowment. Paskal in its *The vulnerability of energy infrastructure to environmental change* (Paskal, 2009) tried to identify some of the most susceptible nodes in the global energy infrastructure. The U.S. Global Change Research Program in *Climate change impacts in the United States: U.S. national climate assessment* (U.S. Global Change Research Program, 2014) covered several topics including the energy supply and use. Kopytko and Perkins in *Climate* *change, nuclear power, and the adaptation–mitigation dilemma* (Kopytko and Perkins, 2011) aimed attention at nuclear power plants. Beyond these papers, we also gave a huge importance to all those documents examined to assess the impacts of climate change on the energy system, because that know-how gives us the basis to detect systems vulnerabilities. Differently from the impact's section, the eye of this assessment will be the system and especially the supply side of it. The analysis of vulnerabilities will be taken from the point of view of the infrastructures and not from the point of view of climate change.

The following assessment of energy system's vulnerabilities will focus especially on the supply part of the system. Climate change is altering and will alter the entire energy system, from energy endowment to energy supply through energy demand. Nonetheless, not all the elements of the energy system show susceptibility to climate change. The electricity generation from renewable or non-renewable resource is affected by vulnerabilities, as the fossil fuel extraction, production, refining, and the transmission, distribution and transfer of energy. Differently, we can say that the other missing parts which constitute the energy system (the energy endowment and the energy demand), are simply vulnerable to specific climatic aspects. In the assessment, we will hint at these vulnerabilities.

Therefore, vulnerability assessment will cover the energy supply side of the system and the vulnerabilities correlated to the other parts. Table 4.2 summarizes the vulnerabilities discussed in the following sections.

Table 4.2 Energy sector vulnerabilities to climate change

ENERGY SECTOR	VULNERABILITY	CORRELATED VULNERABILITY
HYDROPOWER	Water resource availability	Quantity of runoff and seasonal high and low flows Temperature Precipitation Evaporation Extreme events
	Reservoir storage	
	Dependency: glacier – precipitation - runoff	
	Infrastructure safety	Floods Droughts Glacial Lake Outburst Flood (GLOF)
WIND POWER	Large dependence on variations in wind patterns	Impossibility to make adequate predictions of wind characteristics
	Wind characteristics and patterns	Carbon dioxide emissions Rise of temperatures Changes in vegetation Air density
	Impossibility of storage	
	Infrastructure safety	Hurricanes Sea level rise (offshore) Icing
SOLAR POWER	Photovoltaic cell temperature	Irradiance Wind cooling Ambient temperature
BIOMASS AND BIOFUELS	Biomass resource availability	Temperature Precipitation Atmospheric concentration of CO_2 Extreme events: droughts, frosts, hurricanes
	Use in thermal plants and biofuel production	Rise of temperatures Complexity in maintaining a constant temperature Water availability Water properties
WAVE AND TIDAL ENERGY	Availability of wind	
	Large dependence on variations in wind patterns	
	Wind characteristics and patterns	Carbon dioxide emissions Rise of temperatures Changes in vegetation Air density
	Infrastructure safety	Sea level rise
THERMOELECTRIC POWER PLANTS	THERMAL CYCLE EFFICIENCY Increase of ambient air temperature Increase in water temperatures	Location of water intake, location of outlet, fluid velocities, turbulence, pressure changes
	COOLING SYSTEM Water availability Water characteristics Type (once-through/recirculating) Carbon Capture and Storage (CCS)	Once-through cooling system: streamflow condition Recirculating cooling system: water consumption Location of the cooling water intake
	INFRASTRUCTURES Safety Site of building Safety function of safety-related structure	Climate change and extreme events Air and sea temperatures, Wind, Precipitation, Flow rate of rivers, Sea level, Storms
FOSSIL FUEL	Infrastructure safety	Sea level rise, Storm intensity, Wave regime, Air and water temperature, Precipitation pattern, CO_2 concentrations, Ocean acidity, Permafrost thawing
	Efficiency of equipment	Rise of temperatures Water availability
ENERGY TRANSFER	Efficiency of transmission lines and transformers	Rise of temperatures Extreme events, in particular icing and lightning Permafrost thawing
	Infrastructure safety	
	Pipelines	Climate phenomena Soil structure Erosion Subsidence
	Pumping stations and valves	
	Means of transport	Floods Water levels Droughts

4.2.1 Hydropower

The amount of electricity that can be generated from hydropower plants depends on two factors. The first one is the installed generation capacity. The second and most important is the amount of available water. Natural climate variability has great influence on the planning and operation of hydropower systems. It is essential to know the "pace" of the water resource. Most systems are designed taking into account historical records (daily and seasonal fluctuations of water resource) to determine the amount and variability of produced energy. They consider the variation in water inflows trough the seasons, correlated to plant's reservoirs and plant's generation capacity.

In this section we will discuss about the vulnerabilities of hydroelectric generation, focusing during the analysis on three particular main vulnerabilities of the supply hydropower system. Changing climate conditions can affect the operation of existing hydropower systems. Hydropower generation strongly depends on water resource availability: this is the first main vulnerability of the system. Global climate change will add significant amount of uncertainty to the already uncertain design and operation. This uncertainty turns into vulnerability and will affect the generation, hence we already have to take it into account and treat it to protect the future generation.

As already mentioned and characterized, the changing climate is altering the streams of water basins. River flows are variable throughout the year, especially across seasons. Reservoir storage capacity compensates for daily, seasonal and even annual variations in water inflow, enabling the match of electricity generation to variable power demand. Though, climate change, which is modifying the hydrological cycle, puts to the test the existing reservoir storage. The findings about river levels and precipitation patterns, until recently, were considered constant. As the climate change, what were constants are now becoming variables. This causes problems for water storage. Thus, we could say that this is the second main vulnerability of hydropower system.

In the study *Climate change impacts on high-elevation hydropower generation in California's Sierra Nevada: a case study in the upper American river* (California Climate Change Center, 2006), for example, the authors reported that California's hydrology would experience an earlier timing of streamflows. If we stand in the case of having low storage capacity, or otherwise inappropriate to changes, higher inflows in wintertime could lead to greater spillage and less overall energy generation.

The paper *The vulnerability of energy infrastructure to environmental change* (Paskal, 2009) aims to identify some of the most susceptible nodes in the global energy infrastructure. It focuses also on hydropower generation, distinguishing clearly the vulnerabilities of two different kinds of hydropower power plants, the primarily glacier-dependent and the primarily precipitation-dependent.

Glacier-dependent hydro plants are those hydroelectric installations that depend primarily on glacial thaw, such as some in the Himalayas, Alps and Andes. In this kind of plants, the vulnerabilities arise in the reservoirs. At the beginning there is a vulnerability correlated to the size of the reservoirs because water flows may be too big and they cannot fit into reservoirs. Then, once the flows reach a minimal extent, hydroelectric production declines and production vulnerability will grow.

Precipitation-dependent hydro plants are those installations that depend primarily on predictable seasonal precipitation. They will find increasingly difficult to anticipate flow. Dams often supply three purposes: flood control, irrigation and power generation. Hydropower plants rely on predictable rain patterns. If precipitations are inadequate, there will be a loss in generation. The situation can be equally problematic when there is too much water for the design of the installation. If the reservoir fills up in the rainy season and then, owing to changing precipitation patterns, the rain keeps falling into what should be the dry season, the reservoir can back up and impart problems to the upstream zone. If in order to prevent any damage upstream a higher quantity of water is added to the already swollen river, the downstream zones could be flooded and furthermore a certain amount of stored energy would be wasted.

Moreover, there are small systems, which exhibit small run-of-river plants. These plants offer little operational flexibility and, for this reason, these small systems present a great vulnerability. Natural river flow can be highly variable, across seasons and years, and climate change can emphasize this aspect. Reservoir storage capacity can compensate these variations in water flow because it acts as energy storage and copes with climate changes. In some regions snowmelts is part of the hydrological cycle. Snowpack acts as natural reservoir during winter. Climate change will increase river flow in spring and reduce it in summer if the built reservoirs are not designed to manage earlier increased flows: the result could be a waste of energy through spillovers.

The third main vulnerability is related to the safety of hydropower infrastructures. Extreme events like flooding, droughts and Glacial Lake Outburst Flood (GLOF) could lead to physical damage and changes in operations to the hydropower plants and dams. Siltation and erosions follow these events. As written in *Climate change impacts on high-elevation hydropower generation in California's Sierra Nevada: a case study in the upper American river* (California Climate Change Center, 2006), most current dams are built without taking into account the possible impact of climate change and may have lower reservoir capacity to handle frequent extreme events associated with river flow and snowmelt. About dams, if the changes take place slowly over time, the dam safety issue becomes relatively less important as new dams compatible with the new climate can be built.

We could have another vulnerability in those energy systems, where hydro generation is complemented by other power sources. If the electric system is based fundamentally on hydropower, future changes in water availability could lead to an erratic electricity production an even to power shortages. The risk of power shortages must be minimized. These systems present a high degree of susceptibility that must be reduced to keep constantly online the entire energy system. The measure of impact could be assessed in terms of firm power.

Other vulnerabilities of the hydropower system could be associated to the hydropower endowment. The water availability is the main one and it depends on the changing climate. The quantity of runoff and the seasonal high and low flows are vulnerable to the increasing temperatures, precipitation, evaporation and extreme events.

4.2.2 Wind power

The energy produced from wind turbines strongly depends on wind characteristics: wind speed, frequency distribution, average value, directional changes and density.
Climate change will largely affect the characteristics of wind increasing the uncertainty on energy output. Therefore, the main vulnerability of wind power supply is the massive dependence on natural and climate variations in wind patterns.

Another huge weakness, which can be associated to the previous vulnerability, is that wind energy cannot be stored. If we think about hydropower generation, water can be stored and the production can be regularized. This is not possible for wind. We can think to gather the electric energy produced by windmills but we cannot store the wind resource to generate electricity in future, as we can do with water.

There could be a solution to deal with the above-mentioned problems. The remedy should be to have perfectly knowledge of future statistics of wind, to try to match the power demand fluctuations with wind resource or to generally plan energy production. To achieve this target, we would need precise prediction of wind patterns. Nonetheless, it is quite difficult to elaborate global and regional projections of wind changes. Downscaled climate projections have serious limitations when reproducing wind speeds, frequency distribution and directional wind changes. It is much easier to obtain future prediction of temperature changes from climate projections. Thus, another susceptibility is the impossibility to make adequate predictions of wind characteristics.

In the wind power generation sector there is also a vulnerability correlated to the structure of the facilities. Extreme events like hurricanes could heavily stress wind turbines. Windmills can today only operate up to extreme wind speeds of around 25 m/s. At higher wind speeds the strain on the turbine would be too high, which could provoke serious damages to the structures. Offshore turbines are also vulnerable to sea level rise.

Atmospheric icing could hamper production. Global warming facilitates in general the melting of ice. Nevertheless, extreme precipitation associated with low temperatures in north latitudes, for example, could cause ice formation, reducing the performance of wind turbines and even the interruption of the production.

Examining the wind system in its entirety we could observe some vulnerabilities associated with the wind power supply and endowment. Firstly, the generation of electricity is possible only with a specific wind speed. Wind speed must belong to a specific range, which depends on the state of technological progress. Natural variability and climate change cause alterations in the geographical distribution and frequency of wind. Production is consequently vulnerable to the variability of wind speeds.

Wind patterns change due to the contribution of carbon dioxide emissions, from fossil fuel consumption to global warming: emissions are projected to have dramatic impacts on global climate. Consequences of climate change like the rise of temperatures lead to an alteration of wind field characteristics. Changes in vegetation could modify the roughness of soil and consequently the available wind, increasing the uncertainty. Also air temperature affects the generation, because an increase of it leads to a decrease of air density with a commensurate decline in energy density. All these transformation, related to climate change, influences the wind resource, making vulnerable the wind power sector.

4.2.3 Solar power

The photovoltaic cell is the main component of a solar panel, that one which generates electricity.

PV cells are influenced by a factor: they are very sensitive to any changes in temperature. These changes can either be caused by changes in the irradiance or in the amount of wind cooling the solar panel, but especially by changes in the overall ambient temperature. Therefore, solar panels display a vulnerability related to air temperature.

Climate change will rise the temperature of the air and it will also change the composition of the atmosphere, altering the water content and the cloudiness, modifying the atmospheric transmissivity and the amount of the incoming radiation. Therefore, we can state that there is the presence of a vulnerability, but this time related to the endowment of the resource and not to the energy production.

4.2.4 Biomass and biofuels

Biomass could be used as an energy resource, as we know. It can be used either directly via combustion to produce heat, or indirectly after converting it to various forms of biofuel. These two sort of usage present different and common kind of vulnerabilities.

Biomasses used in thermal plants and in liquid biofuel production, show a common vulnerability related to the availability of the biomass resource. The final energy generation is vulnerable to the amount of biomass at our disposal. The quantity depends on various parameters related to climate change, like: temperature increase, water availability, atmospheric concentration of CO_2, extreme precipitation and presence of other extreme events like droughts, frosts and hurricanes. Differently from hydroelectric power, the vulnerabilities of the biomass supply system are not related only on the resource availability (crops for biomass and water for hydropower) but also on the agents which affect the biomass production. Humans influence the achieving of raw materials for biomass system (humans cultivate crops using various techniques, water and fertilizers), whereas they have no influence in the availability of water, the “fuel” of the hydropower sector. For this reason, in the biomass sector we additionally must consider as vulnerability the climate events which affect the crop yield, that is the “fuel” of the biomass sector.

The use of biomass in thermal plants and in liquid biofuel production then presents some different vulnerabilities, related respectively to the changes in air temperature and water availability.

The increase of temperatures induces a specific vulnerability in thermal plants. High temperatures reduce thermal generation efficiency, reducing the generated energy and increasing uncertainty. Therefore, thermal plants, which use biomass as fuel, are vulnerable to high air temperatures. The reduction of generation efficiency and consequently of generated energy could be also caused by water availability. Lower water quantities can reduce the efficiency of the cooling system and consequently the efficiency of the entire plant. We could talk further about the plants’ problems related to temperatures and water availability, but we leave it to a following section in which we will focus specifically on thermal plants and their relative vulnerabilities.

Also biofuel production is vulnerable to climate change. Higher temperatures affect the efficiency of some procedures, like the availability of water. Some processes need high temperatures, so climate change helps the achieve of them. However, normally these processes need a constant temperature, which is hard to keep with high and changing temperatures. Finally, water is crucial for biofuel production. The availability and its properties are very important for it, because the necessary amount and the parameters must be in a very close range which is easy to modify.

4.2.5 Wave and tidal energy

Waves are created through the presence of wind. Consequently, climate change impacts on wind energy have direct impacts on wave formation. Therefore, we can say that all the vulnerabilities of the wind system could show up in the energy supply of the wave system.

Generally, a supply system is vulnerable to the availability of the fuel resource, that are waves and tides in this case. In particular, wind forms waves: for this reason, we can say that the wave system shows a vulnerability to the availability of winds.

Like wind turbines, wave energy converters (WECs) are designed to capture energy from specific wave height, period and direction. Therefore, WECs are vulnerable not only to the availability of wind but also to the characteristics of it, which influence the characteristics of waves.

Because wave energy infrastructures are located in seas and oceans, wave energy converters are also vulnerable to sea level rise.

In literature, there are no references about climate change effects on tidal energy. It is possible that sea level rise could alter the tidal basins ffecting the tidal range but there is no certainty. However, we could assume that tidal energy displays a vulnerability to sea level rise.

4.2.6 Thermoelectric power plants

When we talk about thermoelectric power plants we refer to all those plants which use vapor and/or gas to generate electricity. These power plants use coal, natural gas, oil, nuclear fuel, geothermal energy, solar energy or biomass as fuel, to produce vapor or gas to generate then electricity. Therefore, the power cycles used in these plants are the Rankine cycle or the Brayton-Joule cycle.

Thermoelectric power plants present vulnerabilities in the efficiency of the power cycle and the cooling system, in the facilities and in all the correlated infrastructures. These structures are vulnerable to the changing temperature of air and water, to the availability of water and to extreme events.

Following, we will characterize in details these vulnerabilities using information from some reports and studies like *Climate impacts on energy system* (Ebinger and World Bank, 2011), *The vulnerability of energy infrastructure to environmental change* (Paskal, 2009)*, La gestión del cambio climático. Informe de adaptación* (Endesa, 2013), *Climate change, nuclear power, and the adaptation–mitigation dilemma* (Kopytko and Perkins, 2011), *U.S. energy sector vulnerabilities to climate change and extreme weather* (U.S. Department of Energy, 2013) and all the others used to describe the impacts of climate change in the energy system.

Thermal cycle efficiency

Thermal cycle efficiency of thermoelectric plants is affected principally by increases in ambient air and water temperatures.

The increase in ambient air temperatures and cooling water temperatures will increase steam condensate temperatures and turbine backpressure, reducing power generation efficiency (U.S. Department of Energy, 2013, p.10). The plants based on Rankine cycle are so vulnerable to increase temperatures.

Increasing water temperatures pose other risks to thermoelectric power plants and could reduce available generation capacity. For example, increasing water temperatures put power plants at a risk of exceeding thermal discharge limits, established to protect aquatic ecosystems. Several other factors influence the vulnerability to higher water temperatures of these power plants. These factors include the location of the water intake, the location of the outlet, the fluid velocities of the inlet and outlet, turbulence and pressure changes and natural temperature distributions. For example (U.S. Department of Energy, 2013, p.11), Unit 2 at the Millstone Nuclear Power Station was shut down in August 2012 after temperatures in Long Island Sound exceeded the maximum temperature at which the nuclear power plant is permitted to extract cooling water. However, Unit 3, which pulls water from deeper and cooler waters in the ground, continued to operate.

Cooling system

Thermoelectric facilities use water resources for cooling necessities: hence they are vulnerable to water characteristics.

The water use intensity and the impact of decreasing water availability depends on the type of power plant, cooling system employed, geographic location of the plant and source of cooling water. For example, water withdrawals per unit of power produced are far lower for closed cycle circuits than once-through systems, but the water consumption is higher.

Once-through cooling systems are particularly vulnerable to low streamflow conditions, due to the large volumes of water withdrawn. In contrast, recirculating cooling systems reuse cooling water multiple times than immediately discharging it back to the water source. In recirculating systems that use cooling towers, some of the water evaporates while the rest is reused and sent back to the condenser in the power plant. Recirculating cooling systems, like once-through systems, continually withdraw water. Even if they withdraw notably smaller quantities of water from the source, they can be affected by low flow conditions. Water lost through evaporation in the cooling towers must be replaced, resulting in appreciably higher water consumption than for once-through systems. Thus, less water is consumed by once-through cooling systems, but greater amounts of water are withdrawn, resulting in a greater potential for entrapment and intrusion of aquatic organisms. Increasing water temperatures put power plants at risk of exceeding thermal discharge limits established to protect aquatic ecosystems, resulting in a greater sensitivity to low water conditions.

Another vulnerability associated to the decreasing water availability can be perceived in the placement or location of the cooling water intake structures for the thermoelectric power plant. Cooling-water intake heights will influence the degree to which intake structures are exposed above water levels. During times of drought, river, lake or reservoir water levels may fall near or below the level of the water intakes, used for getting water for cooling, resulting in power production at some power plants being stopped or reduced.

Carbon Capture and Storage (CCS) technologies are not cooling technologies, but we talk about them in this section because, as cooling systems, require a high water consumption. Withdrawal and consumption rates are estimated to be approximately two times higher for coal and natural gas facilities that include carbon CCS, than for those without CCS. Therefore, the plants which use CCS technologies could be more vulnerable to decreasing water availability.

Infrastructures

Normally thermoelectric power plants are placed in regions where there is a large availability of water, to meet the large amount of water for cooling for thermoelectric plants. As a result, they are generally situated in areas that are susceptible to environmental change. Numerous power plants line the coasts and many others are situated inland, near rivers or lakes in low-lying areas or flood plains. All these infrastructures are vulnerable to events correlated to water.

Increasing intensity of storm events, sea level rise and storm surge pose a risk to coastal thermoelectric facilities. Specific vulnerabilities to hurricanes and flooding vary from site to site. Increasing intensity and frequency of flooding set a risk to inland thermoelectric facilities. The intake structures, buildings and other infrastructure at thermoelectric generation facilities that draw cooling water from rivers, are vulnerable to flooding and in some cases to storm surge. They are also dependent on increasingly valuable and variable freshwater supplies.

The International Atomic Energy Agency (IAEA) elaborated the major hazards for nuclear sites, which can in addition be considered for a generic thermoelectric plant. The hazards are temperature of air and sea, patterns, frequency and strength of winds, characteristic of precipitation, flow rates of rivers and rises and anomalies of sea levels. Inland reactors are subject to heat waves, which reduce the power generation, but also to inland floods, which could damage ancillary facilities and put a risk to the stability of the plants. Coastal reactors instead are subject to the rise of the sea level, which can inundate the reactor sites and increase erosion and instability of shorelines. While intense storms combined with sea level rise can produce more severe episodes of flooding and wind damage. Kopytko and Perkins in *Climate change, nuclear power, and the adaptation–mitigation dilemma* (Kopytko and Perkins, 2011) studied the operation of US nuclear power plants during hurricane season. They found that there is a need to design non-safety structures and equipment to withstand the extreme events, or assure that their failure would not disable the safety function of safety-related structures, systems and components, because the structures and equipment are extremely vulnerable to climate change and extreme events.

New commissioned plants in many countries, like in United Kingdom, already present a vulnerability in the facilities correlated to the site of building. Communities do not easily accept a nuclear power station or thermoelectric plant in their region. Thus, in many cases the proposal is to locate the new plants on the same site as the old ones. In UK the government has given assurances that builders would have to "confirm that they can protect the site against flood-risk throughout the lifetime of the site, including the potential effects of climate change". It is however difficult to estimate both the lifetime of the site and the potential effects of climate change. Right from the outset, the new plants present the same vulnerabilities as older plants.

4.2.7 Fossil fuel extraction, production and refining

Oil, natural gas and coal onshore and offshore facilities exhibit various vulnerabilities related to climate change. We can divide these vulnerabilities in two main groups: those ones related to the structure and the maintenance of the infrastructures and those ones related to the efficiency of the processes.

The fossil fuel extraction, the production and the refining are affected by climate change and its consequences in several ways. We can simply state that all these phenomena form lots of vulnerabilities to this huge sector, which are different from each other, according to the type of impact and the affected structure.

The paper *Global climate change implications for coastal and offshore oil and gas development* (Burkett, 2011) indicated six key climate change drivers for coastal and offshore oil and gas development: sea level rise, storm intensity, wave regime, air and water temperature, precipitation patterns, changes in CO_2 and ocean acidity. Hurricanes, for example, can disrupt oil and gas supply and other extreme events, like flooding from sea level rise and storm surges, may cause damages like erosion. All these offshore and low-lying coastal facilities (the oil and gas production and refining) are vulnerable to these climatic events and we must take into account them for adapting the whole system.

The Burkett's paper and the Paskal's one (Paskal, 2009) stress that warming atmospheric temperatures can have various effects on the resource development in the Arctic. Decreasing ice cover may require design changes to counter effects of increased wave action and storm surges like erosion. However, the biggest problem may be the thawing of the permafrost.

Thawing permafrost has the potential to affect severely infrastructure in cold climates. This is a huge vulnerability for the extraction sector. With environmental change, infrastructure problems in cold climates are likely to become more common. We should invest in permafrost and cold climate engineering research to find ways to rebuild Arctic and other cold climate infrastructure in a manner that will be viable over the long term. In addition, the maintenance of the infrastructure is vulnerable to temperature increase.

With regard to the efficiency of refining equipment, climate change may induce a lower water availability which could strongly affect the operation of the facilities. Oil refining is a large water consumption activity. Water demand can be impacted by higher temperatures, as most of refinery's water demand is used in cooling units. Also oil and gas production are vulnerable to decreasing water availability, because the required water for enhanced oil recovery from oilfields and hydraulic fracturing are huge.

4.2.8 Transmission, distribution and transfer of energy

Weather and climate situations can affect the transmission and distribution of power and the transfer of oil, gas and other fuels. This is especially true in the case of transmission lines and pipelines that can extend thousands of kilometers. Even land-based transfers of energy (by road or rail) and water based transfers (by boat or barge) are similarly exposed. In this section we will concentrate on the vulnerabilities of these energy transportation systems, differentiating the vulnerabilities related to electricity grid to the others related to fuel transfer.

The transmission and distribution of electricity through power lines are subject to climate variability: the efficiency of the transmission and distribution depends on various factors, including the temperature of surrounding environment. As reported in *U.S. energy sector vulnerabilities to climate change and extreme weather* (U.S. Department of Energy, 2013), increasing temperatures are expected to raise transmission losses, decrease current carrying capacity and increase stresses on the distribution system. The efficiency of the lines is reduced by higher temperatures, while another effect of the increasing temperatures – the thermal expansion – could produce a significant increase in sag, which could cause several problems. Transmission lines suffer from high temperatures as the electric power transformers. Transformers could even fail causing interruptions of the electric power supply.

The increasing temperatures alongside drought periods could exacerbate the risk of wildfire, which poses a risk to electricity transmission, causing physical damage to transmission line poles and especially to wooden ones.

Other weather phenomena like extreme winds and ice load, lighting strikes, avalanches, landslides and flooding could impact the delivery of electricity though disruption of infrastructure. In particular, excessive icing on overhead lines can cause outages.

In addition, the permafrost thawing, caused by global warming, is considered a risk: much of the existing infrastructures erected in northern regions are located in areas of high hazard potential and could be affected by thaw subsidence.

Summing up, transmission lines and, in general, the whole electricity grid, are highly vulnerable to increased temperatures, droughts, flooding, extreme winds, icing and permafrost thawing.

As regards fuel transfer, first of all we have to say that we must analyze separately the transfer of fuel through pipelines and the transfer through means of transport, because these two kind of transportations present different vulnerabilities.

Referring to *The vulnerability of energy infrastructure to environmental change* (Paskal, 2009), oil and gas pipelines could be damaged by several events like flooding, storms, hurricanes and other extreme events. Even if most pipelines are buried and thus seemingly insulated from the effects of severe weather, there are exposed nodes, such as pumping stations and valves, that are vulnerable to climate phenomena. In addition, it is uncertain how changes in water tables, soil structure, erosion and subsidence might affect pipelines. Existing pipelines may need to be reassessed, especially if they are built on thawing permafrost.

Crude oil, petroleum products like gasoline, coal and corn-based ethanol (blended with gasoline) are transported by rail, boats, barges, trucks and tankers. All these means of transport could be disturbed by climate change: for this reason they could display some vulnerabilities. The most impacted transports are supposed to be the rail and barge systems. Heavy rainfall events will increase flood risk: increased frequency and intensity of flooding events will affect water levels in rivers and ports impeding barge travel: also, it could wash out rail lines, considering that in many regions they follow riverbeds. Besides, reductions in river levels, caused principally by droughts, could impede barge transport of crude oil, petroleum products and coal, resulting in delivery delays and increased costs. Therefore, the transport of fuel is vulnerable to flooding and droughts.

4.3 Indicators of energy sector vulnerability

When considering the state of a system, its development and the need to adjust decisions, policies and actions, measurement is the key.

Since climate variables can affect energy segments differently, mapping vulnerabilities according to these variables and analyzing the impacts on the whole energy system can offer a good measure of climate resilience. Historic information can also provide a basis on which infer the effects of future climate variability according to current patterns of variability. This is especially relevant for the case of extreme events. Such indicators can help in vulnerability assessment, by weighing the importance of specific energy segments in the whole energy system and by providing information about what climate variables are most likely to influence an entire energy system. However, creating a single metric for evaluating the resilience of a system to climate is challenging.

In the World Band study *Climate impacts on energy systems* (Ebinger and World Bank, 2011) the authors indicated that few indicators can be used to assess the resilience of a system based on a comparison of current and future climate. Resilience in resource endowments is related to losses (or gains) in potential production, whereas resilience of energy supply depends also on the efficiency of energy production and conversion. In the first case, comparing total available primary energy in current climate against scenarios of climate change provides a general measure of losses or gains. Then, analyze specific energy segments like hydropower, wind power or oil reserves, would also be important, especially when energy systems have limited diversity.

In addition, the authors displayed other indicators to measure the vulnerabilities of a system and its resilience. For example, the level of diversification of energy production provides an important measure of resilience. Systems that heavily rely on a single energy source can be more exposed to climate impacts; the variety of a system, on the other hand, does not allow the use of a single indicator as good measure of resilience.

Many indicators, based on information about energy systems, can be used to assess the extent to which those systems are vulnerable to climate change. In terms of energy, the fuel shares in total primary and final energy supply, as well as total electricity production and installed capacity, can be useful as indicators. Then, since renewable energy is more vulnerable to alterations in climate, the share of renewable sources in total energy supply and electricity generation/installed capacity is also relevant in assessing climate resilience. For energy supply, variations on overall system efficiency (measured, for example, by the ratio of total final energy to primary energy consumption) induced by climate change, can indicate how energy conversion and transfer can be impacted by climate change, although this measure can show aggregate impacts on energy supply. In addition, there is the need to integrate the understanding of the system's supply vulnerability with some measures of specific energy sources. Projected climate change impacts on the renewable electricity generation capacity factor[1] are a good measure for sources, such as hydropower and wind power generation. Impacts on thermal electricity generation, on the other hand, are better described in terms of

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[1] The net capacity factor of a power plant is the ratio of its actual output over a period of time, to its potential output if it were possible for it to operate at full nameplate capacity.

conversion efficiency or capacity variations. Climate impacts on liquid biofuel production can be assessed through variations in agricultural and conversion productivity.

Variations in energy intensity of a consuming sector can portray a picture of vulnerability from the demand side. The biggest challenge here is to conduct a strict *ceteris paribus* analysis in climate change assessments that are carried out for the long term. The level of information and knowledge about energy relations should be considered as an indicator of resilience, considering that it allows to better understand and act earlier to adapt to climate change impacts.

Two recent studies, *Use of indicators to improve communication on energy systems vulnerability, resilience and adaptation to climate change* (Michaelowa et al., 2010) and *Climate-proofing energy systems* (Williamson et al., 2009) looked at metrics for the vulnerability and resilience of energy systems. They presented a set of indicators to determine the level of vulnerability of a particular energy system, the capacity to implement energy adaptation projects and how successful proposed implementation measures will be in increasing energy system resilience. In the following section we will focus on their works on indicators of the level of vulnerability.

4.3.1 HELIO indicators of vulnerability

The above-mentioned papers aim to contribute to the development of parameters and indicators for energy systems. Based on its experience in applying indicators, HELIO has developed two sets of indicators to respectively measure:

1. The vulnerability of energy systems
2. The effectiveness of adaptation efforts in the energy sector

The second set of indicators is useful for the evaluation of adaptation measures. Hence, these parameters will not be examined in this chapter.

HELIO's philosophy is that the underlying metric – the actual measurement or statistic used – must be generally available for most, if not all, countries. Data collection and vector calculation must be do-able and if calculation is required to derive an indicator it must be simple to do.

Overall the indicators themselves must:

- Be clearly definable, simple to understand, and easily communicated to citizens and decision-makers alike;
- Be relevant to actual or anticipated policies;

- Reflect an important aspect of the social, economic, environmental, technological or governance elements of the energy system;
- Measure something of obvious value to observers and decision-makers;
- Have robustness, durability and long-term relevance.

Prior to display the set of indicators for energy systems' vulnerabilities to climate change, HELIO in *Climate-proofing energy systems* (Williamson et al., 2009) introduces the country-level vulnerabilities. When vulnerabilities are discussed at national level, the discussion is traditionally done around issues of energy supply security and how to improve it. There is little policy formation around the broader context of reducing energy system vulnerability and improving resilience through ecodevelopment strategies, e.g. addressing environmental, social, economic technical and governance issues.

In order to make effective proposed polices and measures, first of all it is necessary to quantify the overall vulnerability state of the country. HELIO's first set of indicators measures the overall vulnerability of a country.

Table 4.3 Country-level vulnerabilities (Williamson et al., 2009, p. 18)

SECTOR	INDICATOR
Environmental	Change in rainfall patterns
	Variation in temperature
Economic	Proportion of households acquiring access to electricity in the last two decades
	Level of increased energy autonomy
Technical	Change in the amount of energy supplied by renewables
	Level of diversity of renewable energy sources and technologies
Social	Change in prevalence of diseases
	Change in employment
Civic (Governance)	Land reform improvement
	Change in public participation in planning process

Finally, the two papers get to define the indicators of vulnerability and resilience.

The principal vulnerability indicators are listed in Table 4.4. The indicators cover all major energy systems. They were picked from the HELIO paper and the Michaelowa et al. one.

Table 4.4 Summary table of vulnerability indicators. Created by author collecting data from (Williamson et al., 2009, p. 31-32) and (Michaelowa et al., 2010, p. 12-15)

SECTOR	INDICATOR	DESCRIPTION
HYDROPOWER	VH1	Expected precipitation change over next 20-50 years (%) and/or probability of floods in each watershed
	VH2	Projected flood frequency over the next 50 years (number of floods that have a greater intensity than a flood with a 100 year recurrence cycle)
WIND POWER	VW1	Number of wind turbines at less than 1 m above sea level
	VW2	Projected change of average wind speed over the next 20 years, based on regional climate models (%)

SECTOR	INDICATOR	DESCRIPTION
	VW3	Projected share of average annual wind speeds over 25 m/s over the next 20 years (at this wind speed most wind turbines have to be switched off)
SOLAR POWER	VS1	Capacity of solar installations already in place (m^2)
	VS2	Expected temperature (°C) increase in the next 20 years relevant for PV capacity
BIOMASS AND BIOFUEL	VB1	Proportion of biomass used for energy purposes (%) in total biomass production
	VB2	Expected precipitation change over next 20-50 years (%)
	VB3	Probability of temperature increase beyond biological heat tolerance of relevant crop over the next 20 years (%). 20 years is the estimated average lifetime of biomass power plants.
	VB4	Projected drought frequency over the next 20 years (number of droughts that would result in a reduction of crop yields by more than 20%)
	VB5	Projected flood frequency over the next 20 years (number of floods that would result in a reduction of crop yields by more than 20%)
	VB6	Number of biomass power plants located at less than 1 m above sea level and situated in an area that has a 100 year flood cycle
THERMAL POWER PLANTS	VP1	Number of thermal (coal, oil and gas) power plants located at less than 1 m above sea level and within the area that would be flooded by a flood with a current recurrence period of 100 years
	VP2	Number of nuclear power plants located at less than 1 m above sea or river level and within the area that would be flooded by a flood with a current recurrence period of 100 years
	VP4	Expected temperature increase of cooling water for thermal (including nuclear) power plants over the next 30 years (°C)
FUEL FROM MINED RESOURCE	VF1	Share of offshore oil and gas installations likely to be hit by a storm of more than 70 m/s gusts over the next 20 years (%). The lifetime of such installations is not well known, but should be shorter than that of power plants. At a wind speed of 70 m/s destruction of plants is likely
	VF2	Share/number of refineries likely to be hit by a storm of more than 70 m/s gusts within the next 20 years (%)
	VF3	Number of coal mines plants located at less than 1 m above sea level and situated in an area than has a 100 year flood cycle
TRANSMISSION AND TRANSFER	VT1	Length of in-country, above-ground transmission and distribution lines (km)

PART C

THE ADAPTATION OF ENERGY SYSTEMS TO CLIMATE CHANGE SCENARIOS

CHAPTER 5

RESILIENCE OF ENERGY SYSTEMS TO CLIMATE CHANGE

Basically, this thesis is divided into three main parts, as already stated many times. The first one examined climate change and the impacts of it to energy system. The second one checked the vulnerabilities of the energy system to climate change. The third, i.e. this specific part, is the main one and it gives the name to the entire thesis. This particular section investigates the adaptation issue and specifically the possible measures which we could put into practice to adapt the energy system – and especially the supply side – to climate change.

The main topic of the third part of the thesis, as we said, is the description of the improvements we have to implement to the supply energy system to adapt it from climate change. Nonetheless, the adaptation of energy system to climate change does not only consist in energy generation improvements. Several more aspects must be considered for implementing a proper adjustment of energy system. The objective of Part C is to discuss emerging practices and tools for managing climate impact, integrating climate considerations and operational practice into planning processes in an environment of uncertainty.

These topics will be explored in two sections. In the first one we will describe the objectives of the adaptation issue and the characteristic of adaptation policies. The second one instead will delineate the adaptation practices we should introduce to make the energy system resilient to climate change.
The structure of this section of the thesis is principally based on the World Bank study *Climate impacts on energy systems* (Ebinger and World Bank, 2011). Some ideas derive from another key study realized by the IPCC Working Group II: *Climate change 2014: impacts, adaptation, and vulnerability* (IPCC, 2014). Several concepts then are supported by other researches carried out by other investigation teams like the UK Climate Impacts Programme (UKCIP), THE United Nations Environment Programme – World Conservation Monitoring Centre (UNEP-WCMC) and the United Nations Office for Disaster Risk Reduction (UNISDR).

5.1 Implementation of climate resilience

The energy sector is at risk from climate change and it is also at risk from current climate variability. Risks handled today, while perhaps are not enough to fully address climate change, will help to address risks into the future. Adaptation measures to climate change and climate variability will surely increase the resilience of energy systems. Thus, to increase the resilience, climate change's adaptation needs to be integrated into energy planning and decision-making processes at all relevant levels.

Remembering the definition of adaptation (*The process of adjustment to actual or expected climate and its effects. Adaptation seeks to moderate or avoid harm or exploit beneficial opportunities*. (IPCC, 2014, p.40)), the targets of the analysis are to reduce the damage from climate change and make resilient the energy system. To reach these objectives it is necessary put into practice some deeds and strategies, which will be delineated in the following sections.

Adaptation to climate change is transitioning from a phase of awareness to the construction of actual strategies and plans in societies (IPCC, 2014, p.871). The combined efforts of a broad range of international organizations, scientific reports and media coverage, have raised awareness of the importance of adaptation to climate change, fostering a growing number of adaptation responses in developed and developing countries. The awareness of the need of adaptation has reached a considerable level: on the other hand, the knowledge about adaptation is still generally scarce, especially in the management of climate risk. Energy risk needs to be assessed and managed from a base of information that is far from perfect. The uncertainties in hydro-meteorology, climate perspective, in short-term and long term predictions will affect the development. Therefore, it is necessary a methodology to improve adaptation in all its dimensions.

In regards, there are probably two basic approaches to guide decisions and actions in risk management and adaptation development (even if we would say that one is not an adaptation approach). Either methods should not use single-scenario assessment of risk. There is nothing incorrect in strict scientific terms in the results produced using single-scenario assessment of risk, but it should always keep in mind that single-realization approaches do not reveal the true extent of the uncertainties involved. Considering that, the two approaches are the *do nothing* and the *proactive*. The *do nothing approach* – which is not an adaptation approach – permits complacency, or more appropriately, lack of awareness. The planning goes along traditional lines, taking climate risks into account as they become clear and managing any issues retroactively. The *proactive approach* on the other hand makes mainstream the risk management. This approach essentially takes into account in advance the risk correlated with climate change in climate strategies, embracing the idea of adaptation.

The following sections explore the desirable outcomes of adaptation decisions and strategies, the main gaps and options to integrate climate risk considerations into energy systems. They recognize the various levels at which integration needs to take place and the multitude of stakeholders involved.

This description will be divided into three parts, underlining the most important characteristics we should take in consideration.

5.1.1 Awareness versus knowledge

Climate change is expected to have a wide range of direct and indirect effects on energy production and consumption patterns. Though, the research and policy-oriented literature are still generally scarce on energy-related climate risk and impacts, not less for management which is emerging. Detailed data on possible climate effects are needed to take decisions about short-term adaptive management and longer-term planning, related, for example, to technological change. It is also important to raise awareness and concern at project, policy and planning level about climate impacts on energy services, as at the wider implications for development. The literature supports identification of key issues and potential options, but the knowledge base is relatively limited for making generalized conclusions on the integration of adaptation options in planning and decision-making. There is a minority of academic literature that provides information on the implementation of adaptation plans, in contrast with the large amount of literature that discusses concepts, strategies and plans of adaptation (IPCC, 2014, p.877).

However, the growing literature on the subject illustrates increasing scientific awareness. An example of this is the study *Raising awareness of climate change. A handbook for government focal points* (United Nations Environment Programme, 2006). In this handbook the authors implemented a checklist for raising awareness. They set a list of steps for planning and organizing a climate change communications strategy, drawn on the wide range of experiences that organizations and government have had in conducting outreach.

5.1.2 Uncertainty in the decision-making

> Responding to climate change involves an iterative risk management process that includes both mitigation and adaptation, taking into account actual and avoided climate change damages, co-benefits, sustainability, equity and attitudes to risk. (Pachauri and Intergovernmental Panel on Climate Change, 2008).
>
> Risk is often represented as the probability of occurrence of hazardous events or trends multiplied by the magnitude of the consequences if these events occur. Therefore, high risk can result not only from high probability outcomes but also from low probability

> outcomes with very severe consequences. This makes it important to assess the full range of possible outcomes, from low probability tail outcomes to very likely outcomes (Pachauri and Meyer, 2015).

A risk-based approach to climate change adaptation can support informed decisions to avoid maladaptation and minimize the risks of over- and under-adaptation. This section describes risk management approaches that are being used to identify adaptive responses and increase the climate resilience of energy systems. It highlights areas where efforts should be strengthened or knowledge gaps exist.

Climate risk management

Risk assessment and management are already important aspects of energy decision making. Energy providers are get used to policy changes, shifting global market conditions, changes in financial variables and climate variability. Energy users cope with price fluctuations as well as near term shortages in energy availability, caused by extreme weather events and damages to energy distribution infrastructure.

Climate considerations are evident especially in planning and investment strategies for renewable resources that depend directly upon climate parameters. Currently, the use of present-day or historical weather and seasonal climate data and information is part of everyday risk management for many utilities and regulators across the world (Audinet et al., 2014). However, the integration of forward-looking information on climate change in decision-making ("climate change adaptation") remains limited. Long term changes in climate and short-term increases in climate variability (as we have seen) are increasingly impacting generation, transmission and distribution of electricity, forcing industry to consider new ways to manage the associated risk.

The UK Climate Impact Programme (UKCIP) developed a risk-based framework (see Figure 5.1) for adaptation decision making in the technical report *Climate adaptation: risk, uncertainty and decision-making* (Willows et al., 2003).

The decision-making framework is composed by eight stages:

1. Identify problems and objectives;
2. Establish decision-making criteria;
3. Assess risk;
4. Identify options;
5. Appraise options;
6. Make decision;
7. Implement decision;
8. Monitor, evaluate and review.

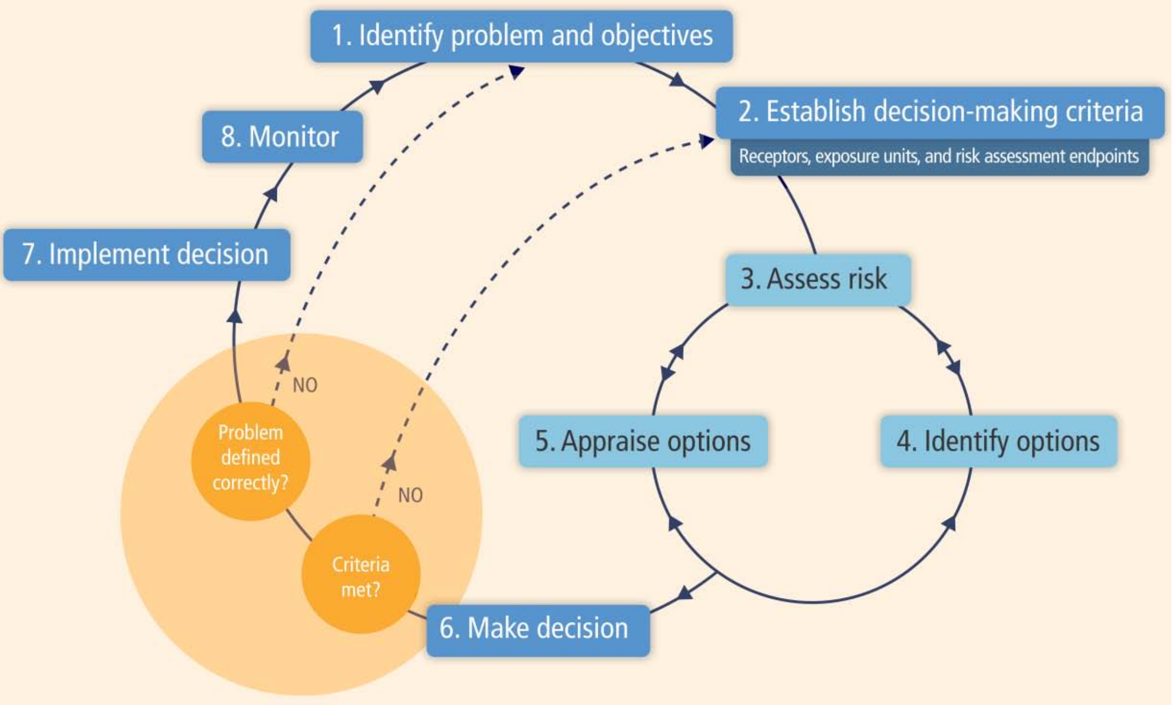

Figure 5.1 A generic framework to support good decision-making in the face of climate change risk (IPCC, 2014, p.851, based on (Willows et al., 2003, p.7))

The iterative risk management process shows a cyclical nature and uses uncertain long-term impacts to develop short-term adaptation priorities and options. This is useful for two main reasons:

1. It provides the short-term policy or project analysis and advice that decision makers need;
2. New information and data can be incorporated continuously as they become available to alleviate constraints on decision-making posed by uncertainty. Decision-making criteria can be revised when new information on costs and feasibility becomes available.

For each stage of the framework there are key issue that decision-maker should consider and questions that should be answered. Stages 1 and 2, for example, define the nature of the decision problem, the decision-maker's objectives and criteria that help differentiate between options. At stage 3 climate change risks associated with the decision are formally identified and assessed, alongside other non-climate risks. Climate change scenarios are an important tool to give information in this stage. At stage 4 the decision-maker should aim to identify options that are robust to climate change and provide the greatest likelihood of meeting the objectives and criteria defined in stage 2. In particular, the decision-maker should try to find "no regret" and "low regret" options. These options are appraised against the criteria in stage 5, to determine the preferred or best option. Stage 6 then demands that the decision-maker forms a judgement, that all issues revealed during the decision-making process have been addressed.

The Energy Sector Management Assistance Program (ESMAP) in its document *Climate vulnerability assessments* (ESMAP, 2009) presented a similar framework for decision-making, to support adaptation of energy infrastructure vulnerable to climate change (Figure 5.2). It created the framework basing it on experience and published guidance from United Kingdom (UKCIP) and Australia.

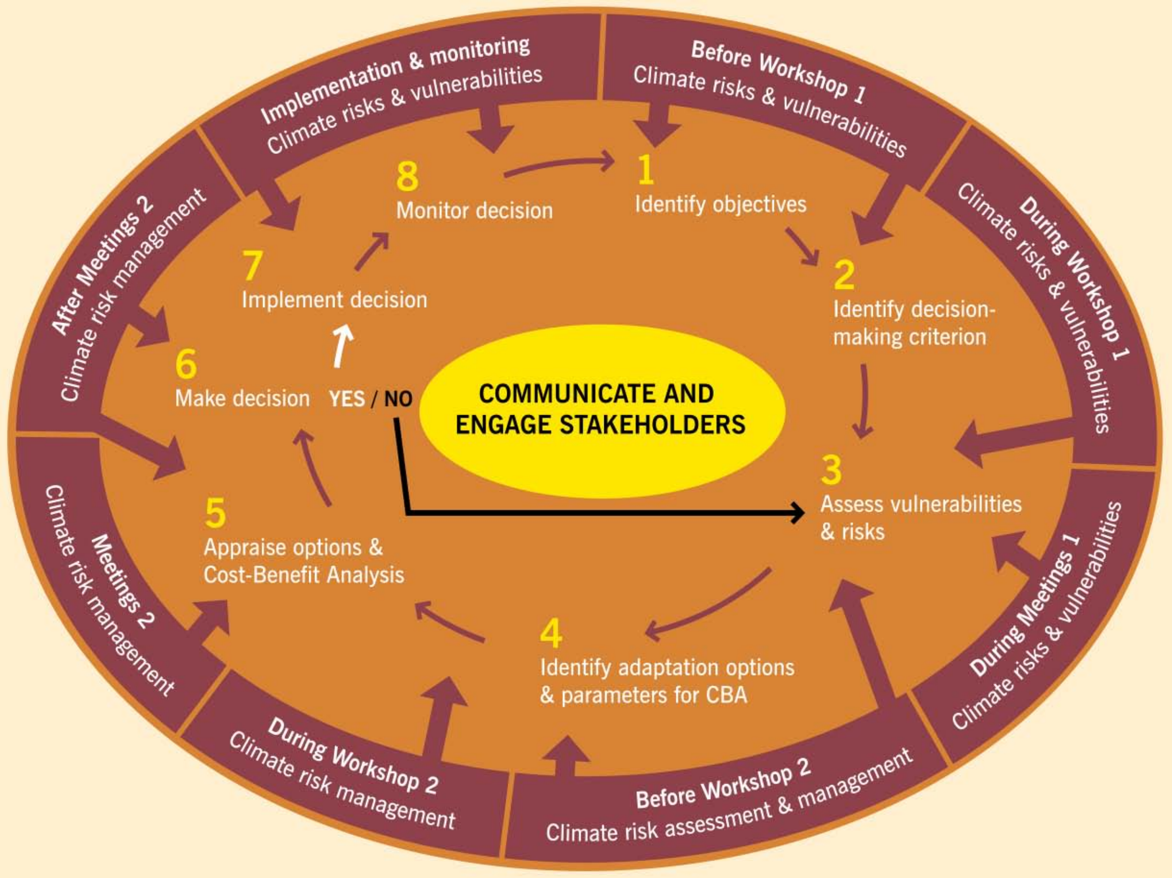

Figure 5.2 Decision-making framework for adapting vulnerable energy infrastructure to climate change (ESMAP, 2009, p.2)

A deeper analysis of the various frameworks for adaptation decision-making reveals that climate risk management requires an interdisciplinary effort, where the tools and knowledge of scientists, energy analysts, economists, policy makers, planners and citizens are combined. Collectively the frameworks highlight at least four features that are relevant for the energy sector: practically, flexibility, compatibility and stakeholder engagement.

In this sense, the United Nations Office for Disaster Risk Reduction (UNISDR) produced the *Hyogo Framework for Action 2005-2015: building the resilience of nations and communities to disaster (HFA)*, a plan to explain, describe and detail the work that is required from all different sectors and actors to reduce disaster losses. It was developed and agreed with the help of many partners, which were needed to reduce risk disaster – governments, international agencies, disaster experts and many others – bringing them into a common system of coordination. In the *Hyogo Framework for Action 2005-2015: building the resilience of nations and communities to disaster. Mid-term review 2010-2011* (United Nations Office for Disaster Risk Reduction, 2011) the authors highlighted the significant progress that has been made over the past years in disaster risk reduction: they also accentuated the fact that the adoption of the Hyogo Framework for Action in 2005 has played a decisive role in promoting this progress across international, regional and national agendas.

Dealing with uncertainty

The energy-system impact relationship is highly complex and uncertain. Uncertainty about the exact nature of climate change impacts at the local and regional level (for example in terms of precipitation and storminess) makes difficult to improve and fine-tune adaptation measures.

Uncertainty exists where there is a lack of knowledge concerning outcomes. It may result from an imprecise knowledge of the risk. However, even when there is a precise knowledge of frequency and magnitude of events there is uncertainty, because outcomes are essentially unknown (Willows et al., 2003, p. 43).

Uncertainty could arise for a lot of reasons: for the estimation of the future growth in greenhouse gas emissions and their concentration in atmosphere, for the estimation of the extent of warming, when regional climatic responses are taken into account, when we consider impacts on various humans and natural systems; etc. Planners and decision makers need local, specific and detailed information about aforementioned cases: however, all those points raise uncertainty.

We could sum up the various types of uncertainty in six categories: "real-world" uncertainty, data uncertainty, knowledge uncertainty, model uncertainty, outcome uncertainty and decision uncertainty. The various uncertainties and their typology could be identified using a risk-based framework, as the UKCIP one showed in the previous section, or using some specific multidisciplinary tools for planning, as suggested by the IPCC in the AR5 (IPCC, 2014, p.883). Some of these tools could be monitoring, modeling or spatially integrated systems with the techniques of GIS. Other ones could be communication tools, like brochures, bulletins, posters, magazines, policy briefs, videos TV, radio broadcasts, Internet and many more. Finally, some more tools could be early warning systems.

Furthermore, climate-sensitive decisions deal with uncertainty: it is useful to know in what way these decisions could be influenced by uncertainty. Some decisions are based on a recognized need to manage current climate variability and extremes and/or to address adaptation in anticipation of longer-term climate change. In this case, awareness and knowledge on climate variability are high. For some other decisions, climate variability and change may be one of many uncertainties that influence the outcome of a decision. In this case, raising awareness among planners and decision makers may be an important first step, to ensure that attention is paid to the potential impacts of climate change.

We could observe then that an inherent risk hits the adaptation decisions and measures: the risk of committing an error in the adaptation. We could distinguish three types of adaptation errors:

- *Under-adaptation*. Too little emphasis is placed on climate risks. It may result from a failure by decision makers to consider or identify climate change or specific climate variables.
- *Over-adaptation*. Climate change or related variables are overemphasized: in practice, practices turn out that are not to be significant or too little weight has been given to non-climate factors compared to climate factors.
- *Maladaptation*. Actions taken (unintentionally) that constrain the options or ability of other decision makers now or in the future to manage the impacts of climate change.

Proper integration of climate risks in decision-making processes will minimize the risk of over-, under- and maladaptation.

Timing and uncertainty

The long-term nature of climate change makes timing an important part of adaptation decisions. The lifetime of a decision is an important consideration when determining whether climate adaptation is needed.

Timing decisions depend on the relative costs and benefits of taking action at different points in time. In particular, decision makers will compare the present value of adaptation now with the present value of adaptation at a later stage. Thus, as described in the document *Economic aspects of adaptation to climate change*: *costs, benefits and policy instruments* (Agrawala et al., 2008), the timing decision depends on three factors. The first is the difference in adaptation costs over time. The effect of discounting would normally favor a delay in adaptation measures, so would the prospect of potentially cheaper and more effective adaptation techniques that might be available in the future. The second factor is the short-term benefits of adaptation. Early adaptation will be justified if it has immediate benefits, for example by mitigating the effects of climate variability. The measures that provide short-term adaptation benefits can be characterized as no- or low-regret options. The third component has to do with the long-term effects of early adaptation. Early adaptation is justified if it can guarantee lasting benefits.

Furthermore, it is useful make a comment on the relation between time, uncertainty and the long-lived infrastructure. Many supply, transmission and distribution investments are large and long-lived. Early adaptation action for long-lived infrastructure investments will generally be less costly and more effective than retroactive maintenance and repairs or expensive retrofitting. Furthermore, substantial investments in energy infrastructure are ongoing or under way in most regions around the world and are expected to continue.

5.1.3 Mainstreaming climate risk management into energy planning

> There is a tall wall between our scientists and our decision makers. Scientists do their research and lob their information over the wall, hoping that somebody on the other side will catch it in receptive hands and act on it. However, what is on the other side of the wall is a big pile of papers and information that the decision makers pay no attention to (Jonathan Foley, 2010, cited in Ebinger and World Bank, 2011, p.93).

This section discusses options to fill knowledge, information, awareness and capacity gaps for climate risk management in the energy sector. It highlights the role of governments and institutions at the local, national and international levels.

Scientific knowledge

Climate risk management presents a knowledge gap: the lack of capacity to model and project climate impacts at local and regional scales is perhaps the most prominent. Government institutions and international research communities have the important task of filling this gap.

Some considerations should be taken into account when prioritizing risk research.

- How far can the risk be reduced through further research and in what time frame?
- How deep are the uncertainties? Do they arise from data needs, a modeling problem, or do we basically not have a scientific understanding of the risk phenomena?
- How do the uncertainties interact with the profile of the risk?

To balance these aspects, we may consider some principles:

- Knowledge needs of various decision makers and stakeholders;
- The cost-effectiveness and likelihood of risk reduction give large uncertainties;
- Investments in decisions with short-term payoffs versus high-risk/high-gain longer-term research.

Guidance for decision makers

Governments, local, regional and national institutions and stakeholders are decisions-makers: they are not the scientists who investigate on climate change, adaptation and risk management. Most of the times, the information obtained by scientists are not comprehensible by decision-makers, which consequently pay no attention to. We need a lot of effort to translate scientific data and knowledge into information relevant to decision making on adaptation.

The correlation between decision-makers and researchers could be summed up by the following outline (see Figure 5.3). As written in the previous paragraph, decision-makers and the research communities have the important task to fill the knowledge task with their skills. Decision-makers should support the scientific community whereas scientists should provide understandable data to decision makers to implement correct adaptation strategies.

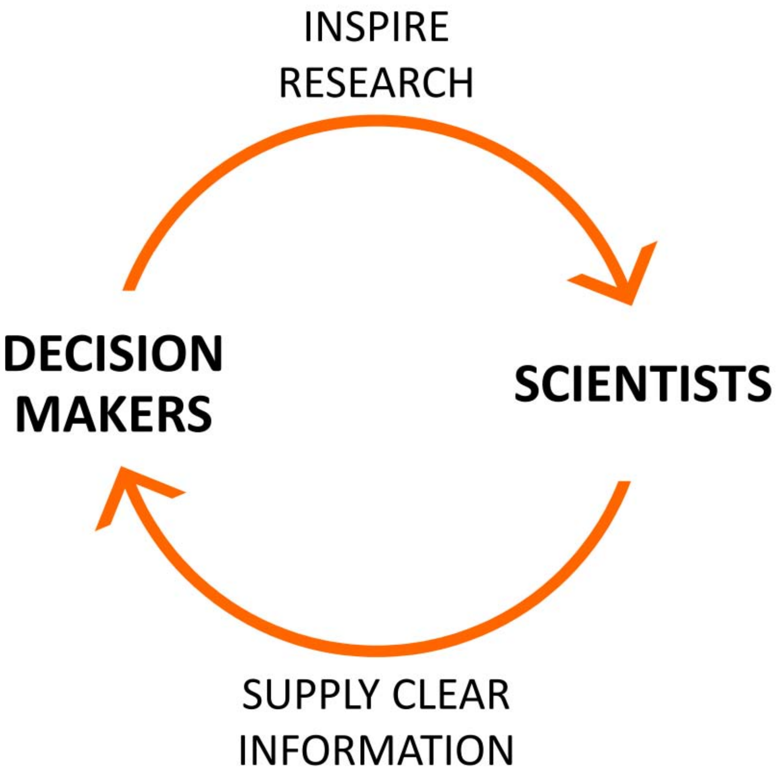

Figure 5.3 The decision-makers/scientists connection. Created by author

Scientists should provide particular comprehensible information to support the capacity of decision makers at various levels. This knowledge should be shown using maps, guidelines and plans to facilitate the decision-makers.

The WGII in *Climate change 2014: impacts, adaptation, and vulnerability. Part A: global and sectoral aspects* (IPCC, 2014) highlighted how limitations of current institutional arrangements within decision-makers restrict the mainstream of climate adaptation. They continued declaring that expanding research on institutional arrangements in at least three key areas can help improve the implementation of adaptation plans in both developed and developing countries. These areas are the multilevel institutional coordination between different political and administrative levels, the institutional rigidity and the coordination between formal governmental and administrative agencies and social and private stakeholders.

The UNEP then in *Raising awareness of climate change. A handbook for government focal points* (United Nations Environment Programme, 2006) asserted that a communication program for decision-makers for addressing climate change could be successful as first step of adaptation planning. The group developed some steps for planning and organizing a climate change communications strategy. These steps are:

1. Set the goals
2. Assess and strengthen the resources
3. Identify the target audiences
4. Approach potential partners
5. Sharpen the messages
6. Deliver the message to the target audiences
7. Evaluate and monitor the results.

Economic assessment

Estimations of the impacts of climate on societies and economies are an effective way (maybe the only way) of catching the attention of central decision makers at international, national and local levels. At present, energy-focused estimates of macro-economic impacts, the economic value of damages and the benefits and costs of adaptation policies are limited. Economic assessment need to be expanded at all levels, including detailed assessment of costs and benefits of adaptation for site-specific investments and national/sector policies.

Integrated development

An effective adaptive response requires that energy systems are considered in the context of development. Adaptation and mitigation policies and actions contribute to this development. Energy sector mitigation and adaptation policies and actions may overlap. Energy diversification, demand-side management and energy efficiency are adaptation as well as mitigation actions. However, some other policies may cause an obstruction between mitigation and adaptation. For example, mitigation policies that hinge on larger share of renewable energy sources are very likely to affect risk management practices, influence technology research and development and affect energy choices. Changing climate parameters may increase energy demand and consumption (for example, for cooling and heating) and extreme mitigation policies may not permit to meet the new energy conditions. If mitigation policies fail to integrate climate impacts on renewable energy source, this could impose severe risks of maladaptation.

CHAPTER 6

THE EMERGING ADAPTATION PRACTICES

For the evaluation of adaptation measures and the formulation of adaptation policies to reduce the damage from climate change, it is essential identifying the vulnerabilities of the energy system to the consequences of climate change. Then, in the global climate change context, adaptation requires a combination of elements that include the availability of economic and natural resources and access to technology, information, infrastructure and institutions.

Adaptation measures can be formulated and can be taken in three different ways. They can be a response to climate change alone or they can be part of a broader set of initiatives. Finally they can be an addition to baseline investments for the purpose of increasing resiliency.

There are similarities between adaptation, in the climate change context, and measures taken by individuals, firms or governments to deal with natural climate variability and variability generated by global climate change. Therefore, dissociating climate change adaptation from energy policy can be complicated, especially when there are many no-regret actions.

Energy systems already take account of some climate risks in their operation and planning. Adaptation measures can further reduce system vulnerability to environmental change, by building capacity, improving information for decision making and integrating climate risks into management and operational decisions.

6.1 Adaptation measures to climate change

This section explores the concept of adaptation and its various attributes in the context of the energy sector. It expands the categories of adaptation measures in the energy sector, which are fundamentally two: the adaptive capacity and the adaption actions. Between the descriptions of the two measure's categories there will be a clarification of the characteristics that an adaptation action must have.

6.1.1 The adaptive capacity

We must understand that adapting to climate change need to be an ongoing process. A critical step in ensuring energy system's resilience is to build adaptive capacity. Building adaptive capacity is crucial for effective selection and implementation of adaptation options.

Quoting *Climate change 2014: synthesis report* (IPCC, 2015, p.118) "*Adaptive capacity is the ability of systems, institutions, humans and other organisms to adjust to potential damage, to take advantage of opportunities or to respond to consequences.*" Specifically, adaptive capacity is the ability or potential of a system to respond successfully to climate variability and change.

The implementation of adaptive capacity needs fundamentally two conditions: improvement of knowledge and increase awareness accessing to information such research, data collecting and monitoring. The second is to provide a supportive framework for action to develop governance, partnerships and institutions.

Improve knowledge system

Generating data and knowledge is a necessary condition for effective action.

Firstly, it has been observed that there is the need to expand on the research side the knowledge of climate change's impacts on energy production and use. There are some general needs, like: provide high-resolution models for local and small regional impact evaluation; research the technologies and practices to save cooling energy and reduce electrical peak load demand; research how the changing regional patterns of energy use impact regional energy supply, institutions and consumers; better understand the effect of changing climate conditions on renewable and fossil-based energy development. Then, there are some other needs related to technology area. Some of these are: better understand space cooling efficiency potential; improve information on the interaction between water demand and use; improve understanding of climate change's impacts and local variability on wind and solar energy production; develop strategies and improve the technological potential of energy supply systems; understand the role of regional interconnections and distributed generation in improving the resilience of electricity supply systems; understand the impact of severe weather events on the sub-sea pipeline systems.

Data collection and monitoring are also important elements of a capacity-building strategy. It is very often stated that "you cannot manage what you cannot measure". Climate adaptation measures in the energy sector are critically dependent on reliable and timely weather and hydro-meteorological observations combined with forecast models and assessment tools specific for the energy sector.

Finally, awareness must be increased. Risk management practices are professionally handled in most cases. But, for a variety of reasons, adaptation needs are unlikely to be included among risks and vulnerabilities.

Supportive framework for action

Successful adaptation involves collaboration across a multitude of interested partners and decision makers: international, national and local government, the private sector, nongovernmental organizations, community groups and others.

National and transnational governments can provide a clear policy framework to guide effective adaptation in the medium and long term. Local public institutions (local governments), civil society institutions (producer organizations) and private institutions (private businesses) have an important operational role because adaptation action is inevitably, mainly locally. At the business level, energy companies list physical risks as a concern.

The WGII of the IPCC strengthened this thesis asserting that planning and implementation of adaption follow formal institutions associated with regulations, policies and standards created and enforced by government actors. They also added that the planning and implementation require the participation of informal institutions through interactions among stakeholders, according to cultural, social and political conditions in societies.
Institutional dimensions may both enable and limit adaptation planning and implementation. Currently institutional arrangements restrict the mainstreaming of climate adaptation through some institutional barriers, which in general are seen as dynamic and context-dependent across sectoral, spatial and temporal scales. This means that how a particular institutional barrier operates to either strengthen or limit the planning and implementation of adaptation, can vary both between and within countries, depending on case study locations. Hereinafter we illustrate five of the most commonly emphasized barriers or enablers of institutional change.

1. The importance of multilevel institutional coordination between different political and administrative levels in society is increasingly cited as challenging in both developing and developed countries. Several studies report that climate adaptation is inhibited by levels and actors, without being conscious of the roles and responsibilities. There are few national requirements or guidelines to help local governments approach climate adaptation. In addition, climate change does not possess clear institutional characteristics as a municipal professional area. Further, the literature shows that the lack of clear national agendas and incentives may burden local governments differently, based on their different capacities.
2. Literature shows that key actors, advocates and champions are decisive for initiating, mainstreaming and sustaining momentum for climate adaptation planning and implementation in different national settings. Key actors can be particularly important in the absence of strong national level policies and strategies.
3. The horizontal interplay between actors and policies operating at similar administrative levels is seen as key in institutionalizing climate adaptation. Local governments and administrations consist of different professional silos with their own internal norms, values and priorities. The institutional rigidity of existing administrative and political sectors creates unfortunate compartmentalization.

Climate adaptation is seen as the isolated task of a singular sector that may hinder mainstreaming and horizontal coordination across sectors and departments.

4. The need to acknowledge political dimensions in planning and implementation is highlighted in several studies, both in developing and developed countries. Politicians have not recognized climate adaptation as being politically crucial enough to elevate on the policy agenda. Subsequently, they identify a tendency to prioritize other political concerns (often more short-term tangible issues).
5. Improved coordination between formal governmental and administrative and private stakeholder is highlighted in the literature. Private sector involvement is often seen as a way to increase the efficiency of climate adaptation.

6.1.2 Diversification of adaptation actions

The primary objective of adaptation in energy system could be interpreted as guaranteeing the supply of energy and balancing production and consumption throughout time and space. The process of adapting to climate change is complex and consists of a multitude of behavioral, structural and technological adjustments. In this section we differentiate adaptation actions, basing them on a set of attributes illustrated in *Climate impacts on energy systems* (Ebinger and World Bank, 2011).

- ***Timing of action***
  Adaptation measures may be *proactive* or *reactive*. A proactive approach in energy systems aims to reduce exposure to future risks. A reactive approach instead aims to alleviate impacts on installed technologies or supply systems. An example could be re-inforce existing energy infrastructure with more robust control solutions that can better respond to extreme-weather-related service interruption.
- ***Temporal scope***
  Adaptation measures can be *short term* or *long term*. The distinction between short-run and long-run adaptation has to do with the pace and flexibility of adaptation measures.
- ***Ability to face associated uncertainties and/or to address other social environmental or economic benefits***
  - *No-regrets*. Adaptation measures whose socioeconomic benefits exceed their costs;
  - *Low-regrets*. Adaptation measures for which the associated costs are relatively low and for which the benefits under projected future climate change may be relative large;

  - *Win-win*. Adaptation measures that minimize social risk and/or exploit potential opportunities, but also have other social, environmental or economic benefits.

- ***Location***

  Adaptation measures can be *localized* or *systemic*. Impacts from climate change are frequently local, but there are also cases where the impacts are systemic, such as when climate impacts affect resource endowments.

- ***Nature of agents involved in the decision making***

  Adaptation measures can be *private* or *public*. Note that this distinction can also be referred to autonomous or "market-driven" versus planned or "policy-driven" adaptation. Most of the energy infrastructure in developed countries is privately owned. However, since these economies depend significantly on reliable supplies of energy, governments have to ensure that this energy infrastructure is resilient to climate change.

6.1.3 The adaptation actions

We could easily say that this section is the core of the entire thesis. In this section we will delineate the responses, measures and actions we should implement to adapt energy systems to climate change scenarios.

The focal point of this portion is the description of all those adaptation measures we should put into practice to reduce the vulnerabilities of energy systems. As already said, the thesis is divided into three main parts: description of the impacts of climate change on energy systems, identification of the vulnerabilities of the system to climate change and finally characterization of adaptation measures to reduce the vulnerabilities. This is the last part and here we make clear the entire purpose of the thesis.

Nonetheless, this part of the thesis does not only be formed by the actions we should undertake against the vulnerabilities of the supply side of the energy system described in Chapter 4, but it presents also other actions regarding the demand side of the energy system and the management of adaptation. We begin talking about the demand side of the system, then about the supply side and finally about the adaptation management. But first, we explain the subdivision – that we did – of the adaptation responses.

Adaptation responses to system's vulnerabilities can be classified as technological, behavioral or structural, according to *Climate impacts on energy systems: key issues for energy sector adaptation* (Ebinger and World Bank, 2011). Adaptation measures could be also divided into engineering and non-engineering options as stated by *Climate risk and adaptation in the electric power sector* (Asian Development Bank, 2012). The terms technological and behavioral and the terms engineering and non-engineering essentially have the same meaning.

Technological or engineering responses concern the new or adapted technologies to reduce the vulnerability of energy assets or strengthen their resilience to the consequences of global warming. Some responses include physical protection devices and better design of assets in the planning stage through improved design standards. In some circumstances the response could be relocate or retrofit extremely vulnerable existing infrastructure, decentralize generation systems or develop new technologies like smart grids to accommodate renewable sources with intermittent generation in existing grids.

Behavioral or non-engineering responses instead refer to the reconsideration of the location of investments. It may be cost-effective to implement some specific actions, like put in place more robust operational and maintenance procedures, improve and better coordinate land use planning, improve energy security through policies and enforceable regulations. Others could be to decentralize local planning and generation, integrate climate change and disaster management planning, improve forecasting of demand changes and supply-demand balance with climate change, integrate power sector planning into other sectors' planning and improve localized models used to predict storms and flood hazards.

The technological and behavioral, or engineering and non-engineering adaptation measures in the energy sector intended to minimize negative impacts due to long-term changes in meteorological variables and extreme events. Substantially, these responses are those measures which counteract the vulnerabilities of energy system to climate change.

The structural responses cited by Ebinger and World Bank include all actions which require sector wide changes, including the deployment of sector wide incentives. One example is the adoption of policy frameworks to facilitate the internationalization of adaptation concerns in energy systems, either through the set-up of economic or fiscal incentives.

Table 6.1 summarizes the measures we will discuss hereinafter. The terms we will use to divide the various adaptation measures will be engineering and non-engineering. Most of the adaptation measures have been identified in four reports: *Climate risk and adaptation in the electric power sector* (Asian Development Bank, 2012), *Climate impacts on energy systems: key issues for energy sector adaptation* (Ebinger and World Bank, 2011), *Use of indicators to improve communication on energy systems vulnerability, resilience and adaptation to climate change* (Michaelowa et al., 2010) and *Climate-proofing energy systems* (Williamson et al., 2009). Those information or adaptation practices not identified in the aforementioned documents will be punctually specified.

Table 6.1 Adaptation measures for energy demand and energy supply systems to climate change

VULNERABLE ELEMENTS		**ADAPTATION MEASURES**	
		ENGINEERING MEASURES	**NON-ENGINEERING MEASURES**
DEMAND	ELECTRICITY END USE	➢ Increase generation (MWh) and capacity (MW) ➢ Improve the energy efficiency of energy supply ➢ Improve end-use efficiency for buildings, facilities and energy-intensive appliances and machinery ➢ Reduce the need of cooling, increase cooling efficiency and decrease internal heat gains ➢ Implement energy storage technologies as further option to shift electricity consumption away from peak hours	➢ Require minimum energy performance standards for new commercial buildings ➢ Require a wide range of electricity-using appliances with labelling and certification ➢ Require and enforce energy performance standards ➢ Develop legislation and access to finance for energy service companies ➢ Set minimum standards for industrial electrical motors; ➢ Consider subsidized programs for mass replacement of incandescent lights, and replacing old inefficient refrigerators with never efficient models ➢ Adopt the ISO global energy management standard ➢ Consider the possible use of solar photovoltaic rooftop panels to reduce summer building cooling loads
SUPPLY	HYDROPOWER	➢ Design more robust dams for heavier flooding and extreme events ➢ Increase dam height to accommodate increase river flow extremes ➢ Construct or augment water storage reservoirs ➢ Restore and better manage upstream land ➢ Construct small dams in the upper basins if flow is expected to increase ➢ Adapt or expand installed capacity to accommodate increase in flow regime ➢ Modify canals or tunnels to better handle changes in water flows ➢ Modify spillway capacities and install controllable spillway gates ➢ Modify the number and type of turbines that are better suited for expected water flow rates and more resilient to performance reductions and turbine lifetime ➢ Design regional integration through transmission connections ➢ Siting plants in locations non-threatened by Glacial Lake Outburst Flood (GLOF) risks ➢ Promote the development of smaller plants to respond to GLOF risk	➢ Analysis to estimate likely range of projected climate variations over hydro lifetime ➢ Identify cost-effective designs (new plants) and modifications (existing plants) to deal with specific risks identified for the site ➢ Adapt and implement in plant operation to account for changes in river flow patterns ➢ Relocate based inflow on changes in flow regime ➢ Optimize reservoir management and improve energy output by adapting to changes in rainfall or river flow patterns ➢ Operational complementarities with other sources (for example natural gas) ➢ Develop improved hydrological forecasting techniques and adaptive management operating rules ➢ Develop basin-wide management strategies that take into account the full range of downstream environmental and human water uses
	WIND POWER	➢ Construct turbines that can operate at higher wind speeds and gusts ➢ Design a foundation which support the turbine where there are changes in permafrost conditions ➢ Design offshore turbines to withstand expected increases in wind-sea wave forces ➢ Use taller towers to capture the stronger winds at higher altitudes ➢ Consider the development and commercialization of vertical axis wind turbines ➢ Consider the effects of extreme low and high temperatures in turbine ➢ Implement passive and active methods to reduce icing. Passive method: design blades with reduced ice accumulation. Active method: blade heating ➢ Integrate increased amounts of wind energy into the grid	➢ Choose sites for new infrastructures, or relocate existing turbines in sites that take into account expected changes in wind speeds during the lifetime of the turbines, as well as sea level rise and changes in river flooding ➢ Siting procedure to take into account expected changes in wind speeds and sea –level rise during the lifetime of the turbines ➢ Ensure the presence of rapid emergency repair teams ➢ Develop insurance schemes for long-term wind power yields and damages ➢ Develop meteorology-based weather/climate forecasting

SUPPLY	SOLAR POWER	➢ Assure structures are strong enough to withstand higher winds ➢ Specify stronger mounting structure, and cabling and components that can deal with high moisture content and flooding ➢ Specify heat-resistant PV cells and module components designed to withstand short peaks of very high temperature ➢ Use designs that improve passive airflow beneath photovoltaic mounting structures ➢ Where snowfalls are heavy or likely to increase, assure free space so that snow can slide off the panel ➢ Where solar energy is likely to become more diffuse, with changes in cloud cover, rough surfaced photovoltaic modules are more efficient ➢ Where clouds are likely to pass over modules more quickly, consider micro-inverters for each panel to improve stability and increase power output ➢ Consider distributed systems which can improve grid stability ➢ For any tracking solar system for CSP, the motors and their mounting must be especially robust wherever stronger winds are expected ➢ Avoid tracking systems where cyclones are expected to increase in strength (CSP) ➢ Consider forced air and liquid coolant systems where temperature will increase (CSP) ➢ Where water shortages are expected consider air cooling (CSP) ➢ Use evacuated tube collectors for thermal heating because they do not suffer from ambient temperature problems ➢ Use engineer evacuated tube collectors with higher resistance to hailstorms ➢ Use evacuated tube collectors than flat plate collector when there is more diffuse than direct insolation	➢ Develop meteorology-based weather/climate forecasting ➢ Where possible, site solar photovoltaic, CSP and thermal systems where expected change in cloud cover are relatively low ➢ Choose locations with lower probability of dust, grit and snow of practical ➢ For locations where temperature increases or significant heat waves are expected, choose modules with more heat-resistant photovoltaic cells and module materials designed to withstand short peaks of very high temperature ➢ For distributed solar systems, make available mobile repair teams to ensure functioning of systems after damage from extreme events
	BIOMASS AND BIOFUELS	➢ Expand irrigation systems or improve the efficiency of existing irrigation to counteract drought impact if sufficient water is available from sources outside drought-hit area ➢ Use unconventional sources if there is no availability of conventional water resources ➢ Protect against floods by building dykes and improving drainage ➢ Expansion of rainwater harvesting, water storage and conservation techniques, water reuse and desalination ➢ Improve water harvesting and use ➢ Improve soil and nutrient management ➢ Increase the robustness of biomass power plants	➢ Use of salt-tolerant pants (halophytes) – including varieties of sugarcane, millet and corn that grow in brackish water on saline land ➢ Adjust crop management and rotation schemes ➢ Adjust planting and harvesting dates ➢ Introduce soil moisture conservation practices to improve soil fertility ➢ Relocate crops in areas with lower risk of flooding and storms ➢ Implement early warning systems for seasonal rainfall and temperature anomalies ➢ Support emergency harvesting of biomass in case of an imminent extreme event ➢ Provide crop insurance schemes ➢ Control pests and diseases because climate change appears to be altering them ➢ Improve ecosystem management ➢ Implement efficient harvesting and early transformation of agriculture produce to reduce post-harvest losses and preserve crop quantity and quality
	WAVE AND TIDAL ENERGY	➢ Devices need to be engineered to withstand extreme waves by being massive ➢ For sea wave floating systems, consider designing for 50-year freak waves ➢ For sea wave anchorage systems, design them to be oriented in the wave direction rather than across the wave front to reduce vulnerability to severe stresses ➢ Consider protection mechanism against storm ➢ Raise level of barrage basin walls for tidal systems ➢ For OTEC, construct larger pipes to increase volume of water to the surface ➢ Design deep-sea pipes to withstand greater stresses	➢ Consider onshore or nearshore systems to produce electricity, because they are less vulnerable to storm damage, although the power available is less than further out at sea

SUPPLY	THERMOELECTRIC POWER PLANTS	➢ Develop and implement higher structural standards for new or renovated buildings ➢ Build concrete-sides buildings instead of metal because they are more resistant to wind and corrosion ➢ Raise level of structures ➢ Develop flood control where floods are likely to increase. Implement embankments, dams, dykes, reservoirs, polders, ponds, relocated flood defense, barriers and higher channel capacity ➢ Construct improved coastal defenses (seawalls and bulkheads) ➢ Improve drainage and reroute water pipes ➢ Protect fuel storage including stockpiles ➢ Change the cooling system from a once-through to a closed-circuit ➢ Redesign cooling facilities: recover water from condense and heat exchangers, reduce evaporative losses, increase secondary or wastewater usage, construct dry cooling towers ➢ Increase volume of water treatment works and develop new water sources ➢ Install additional cooling towers and modify cooling water inlets at coastal locations ➢ If cooling water is unavailable with climate change, air-cooled systems could be used ➢ Use dry or hybrid cooling systems with lower water requirements ➢ Develop more efficient pumps and heat exchangers	➢ Choose better locations (less exposed places) to build new thermal plants ➢ Concentrate investment in locations where temperatures are likely to be cooler ➢ Decentralize generation ➢ Invest in more cooling capacity and in different cooling technologies ➢ Invest in more spare production capacity and more network capacity ➢ Require more stringent safety investments ➢ Develop and implement higher structural standards for new or renovated buildings ➢ Incorporate gradual sea level rise, increased storms events and associated tidal surges into design criteria ➢ Formulate long-term strategies to respond to climate-related disruption ➢ Restore/afforest/reforest land
	FOSSIL FUEL EXTRACTION, PRODUCTION AND REFINING	➢ Build or enlarge reservoirs of water to reduce flooding risk in new and existing mining developments ➢ Reassess flood-prone areas and elevating buildings or vulnerable components ➢ Build flood-proofing buildings ➢ Power plants and pumps should preferably be sited where there is an adequate supply of cooling water ➢ Consider air cooling as an alternative to water cooling ➢ Build or improve dykes, berms and spillways onshore ➢ Build or enlarge reservoirs of water to reduce water shortages ➢ Develop or reroute water source ➢ Improve the robustness of designs, particularly offshore installation that are vulnerable to storms	➢ Site future mines in areas that have a limited exposure to flooding or drought risk ➢ Adopt techniques that slow, steer and block water flows ➢ Carry out flood hazard assessments ➢ Improve models used to predict storms
	TRANSMISSION, DISTRIBUTION AND TRANSFER OF ENERGY	➢ Reinforce existing T&D structures and build underground distribution systems ➢ Where stronger winds are expected, strengthen distribution poles with guy wires ➢ Where lightning strikes may increase, include lightning protection ➢ Specify more effective cooling for substations and transformers ➢ Design improved flood protection measures for the infrastructure ➢ Build a resilient high-capacity transmission system ➢ Use smart transformers which control the flow of electricity to stabilize existing aging power grids ➢ Develop and use smart grids ➢ Design more flexibility into T&D networks, allowing increased rerouting during times of disruption ➢ Reduce pressure on the grid through distributed, decentralized energy generation ➢ Take care to maintain grid stability	➢ Require higher design standards for distribution poles and towers ➢ Invest resources into building a resilient, high-capacity transmission system ➢ Improve system management through investing in smart grids ➢ Forbid the construction of power lines near dikes and ban permanent trees next to existing dykes ➢ Specify Information and Communication Technology (ICT) components that are certified as resilient to higher temperatures and humidity, and design improved redundancy into ICT systems, including wireless transmission better able to handle high temperatures

6.1.3.1 Demand side adaptation measures

Before dealing with the main topic of the section – the characterization of the specific adaptation measures against the vulnerabilities listed in Chapter 4 – we will discuss those general adaptation measures associated with electricity end use demand.

For electricity end use, the adaptation measures, necessary to cope with increased energy demand with temperature rises, could be engineering and non-engineering. These adaptation measures, as many others we will display, have to take into account different more problems related to climate change, as mitigation. The implementation of certain measures must be pondered on many aspects and not only on adaptation targets. This consideration could be already applied in the engineering measures.

Engineering measures

- Increase generation (MWh) and capacity (MW) to meet increased demand (business as usual approach);
- Improve the energy efficiency of energy supply (generation, transmission, distribution system improvements);
- Improve end-use efficiency for buildings, facilities and energy-intensive appliances and machinery. Reduce the need of cooling, increase cooling efficiency and decrease internal heat gains;
- Implement energy storage technologies as further option to shift electricity consumption away from peak hours. The main storage technologies are electrical energy storage (capacitors) mechanical energy storage (compressed air energy), chemical energy storage (batteries) and thermal energy storage (sensible heat systems such as steam accumulators).

The increase of generation and capacity should be intensely pondered. The level of diversification of an energy system has a profound influence on its resilience to climate impacts. Having alternatives means to reduce the vulnerability of the sector as a whole to a specific set of climate impacts. Relying on a single source of energy can make an energy system vulnerable in the case of an adverse impact from climate change. Broadening the range of power plant types and fuels in the generation mix and using a mix of centralized and decentralized supply patterns will help to increase the flexibility of the system and its resilience to more variable climatic conditions.

Non-engineering measures

There is a large range of technical and policy demand-side energy efficiency measures available, that can reduce energy demand and the need for investing in new capacity. Many may require new regulations and their enforcement to have a discernible impact; they also may be more effective if power utilities are required to take a proactive role in demand-side management. Policy measures include the following:

- Require minimum energy performance standards for new commercial buildings and a wide range of electricity-using appliances with labelling and certification programs;
- Require and enforce energy performance standards;
- Develop legislation and access to finance for energy service companies, with remuneration based on energy actually saved through an investment, reducing the risks of undertaking energy efficiency initiatives and measures;
- Set minimum standards for industrial electrical motors;
- Consider subsidized programs for mass replacement of incandescent lights with more efficient compact fluorescent lights or light-emitting diodes (LEDs) and replacing old inefficient refrigerators with never efficient models;
- Adopt the International Organization for Standardization global energy management standard;
- Consider evaporative cooling, which may be effective even in temperature climates as temperatures rise and summers become hotter and drier;
- Consider the possible use of solar photovoltaic rooftop panels to reduce summer building cooling loads.

Then, the report *Adaptation of California's electricity sector to climate change* (Vine, 2008) shows the portfolio of adaptation strategies for California's electricity sector, including mitigation, adaptation, technological development and research, in which California's utilities have always had a fundamental role. These strategies are:

- **Reducing peak demand increases**
  The electricity system can respond to increase in peak demand in two primary ways: by reducing the magnitude of increased peak demand through energy efficiency programs and by increasing the resiliency of the energy production system to respond to these peaks.
  California's state and local government institutions and utility companies have extensive programs to promote the use of high efficiency machinery, as high efficiency air conditioners. In addition, alternative technological solutions to air conditioners are being studied. For example, in some areas of California where air conditioners are used for only few hours in the summer, households do no need to use an air conditioner if the house is designed and built with energy efficiency principles in mind (e.g., thermal mass, use of natural cooling, well-insulated, evaporative coolers, etc.).
  Public information programs can also play a large part in mitigating the effects of energy demand increases. And moreover, California's utilities have been the leaders

nationally in promoting energy efficiency. As reported in Vine (2008), since 1975 the energy savings from the utilities' energy efficiency programs and from the state's building and appliance standards have supplanted the need for a minimum of 24 new large-scale (500 MW) power plants.

- **Improving the generation system's ability to respond to peak demands**
  The adaptability of the energy system will be enhanced if future installations can be designed with built-in flexibility to accommodate the span of potential climate impacts. Energy sources in the future may be integrated increasingly with buildings (e.g., zero energy new homes).
- **Enacting mitigation policies that enhance adaptation potential**
  California has been a leader in implementing energy legislation and policy that affect how the public and private sector will manage climate change. California is expected to continue this leadership role. Local governments in California have also been national leaders in preparing for climate change by implementing policies that primarily have a mitigation focus but will also provide adaptation benefits.
- **Increase research, demonstration and development (RD&D) to support energy sector response**
  While existing technologies are available for California to use as part of its adaptation response, there is a need to develop a portfolio of robust energy efficiency technologies as part of a major RD&D effort.

6.1.3.2 Supply side adaptation measures

This part of the section describes the specific adaptation measures related to the vulnerabilities of the supply side of the system and the vulnerabilities correlated to the other parts of the energy system. The description will start from electricity generation through renewable and non-renewable resources: then it will get to fossil fuel extraction, production and refining and transmission, distribution and transfer of energy.

Hydropower

Hydropower plants have a long-term lifetime, of about 50 or 100 years: for this reason, is fundamental assess all the changes in climate that might affect the output and the operation of the generation plants.

Carrying out an initial analysis based on recent climate change models can improve confidence and reduce costs that may be unnecessary for the proposed hydropower development. Similar studies might identify cost-effective modifications of the existing infrastructure (not design changes) for adapting the system to climate change. These analyses are useful not only for the infrastructure safety, but especially for system operation.

Anyway, hydropower plants are normally robust and an increase in the strength or frequency of extreme events like storms or cyclones only marginally increase the risk of destruction (Asian Development Bank, 2012, p. 22). Many more problems arise in the operation and management of the entire system due to changes in hydropower endowment. So both engineering and non-engineering measures are essential for adapting the hydropower generation system to climate change in general. Specifically, non-engineering measures can be integrated into existing or future developments and typically require the involvement of numerous stakeholders within the river basin.

Engineering measures

- Design more robust dams and infrastructure for heavier flooding and extreme events;
- Increase dam height and enlarge floodgates to accommodate increase river flow extremes (also for glacier melting) and variability;
- Construct or augment water storage reservoirs and change reservoir management;
- Restore and better manage upstream land including afforestation to reduce floods, erosion, silting and mudslides;
- Construct small dams in the upper basins if flow is expected to increase;
- Adapt or expand installed capacity to accommodate increase in flow regime;
- Modify canals or tunnels to better handle changes in water flows;
- Modify spillway capacities and install controllable spillway gates to flush silted reservoirs
- Modify the number and type of turbines that are better suited for expected water flow rates. Make the turbines more resilient to performance reductions and lifetime due to higher suspended sediment loads;
- Regional integration through transmission connections. As reported in *Amazon and the expansion of hydropower in Brazil: Vulnerability, impacts and possibilities for adaptation to global climate change* (Soito and Freitas, 2011) the hydraulic operation of reservoir systems is always directed towards energy optimization and meet the multiple uses of water. From the perspective of energy optimization, the existence of reservoir accumulation provides important energy exchange between regions of the country, made through the Brazilian transmission network. Figure 6.1 shows the energy exchanges between regions in Brazil;
- Siting plants in locations non-threatened by Glacial Lake Outburst Flood (GLOF) risks. This adaptation measure is typical of those regions in the world where there are hydropower plants which are glacier-dependent. In the document *Development and climate change in Nepal: focus on water resources and hydropower* (Agrawala et al., 2003) it is recommended to move proposed hydropower plants to alternative locations to reduce vulnerability of GLOF risk. This risk is relevant to the construction of both small-scale hydropower plants and large-scale ones: the former because they are often

located in close proximity to potential sites, the latter because of the danger of damage and much faster rates of siltation than design can cope with.

Another adaptation response to GLOF risks is to promote the development of smaller plants, which would spread the risk of a catastrophic flooding event and avoid damage to a huge plant with significant sunk cost.

Figure 6.1 Energy exchange between regions in Brazil (Soito and Freitas, 2011, p.3174)

Non-engineering measures

- Analysis to estimate likely range of projected climate variations over hydro lifetime;
- Identify cost-effective designs (new plants) and modifications (existing plants) to deal with specific risks identified for the site;
- Adapt and implement in plant operation to account for changes in river flow patterns;
- Relocate based inflow on changes in flow regime;
- Allow for increased flows from glacier melting if they are likely to persist over the technical lifetime of the system's increased capacity;
- Optimize reservoir management and improve energy output by adapting to changes in rainfall or river flow patterns;
- Operational complementarities with other sources (for example natural gas);

- Develop improved hydrological forecasting techniques and adaptive management operating rules;
- Develop basin-wide management strategies that take into account the full range of downstream environmental and human water uses.

Wind power

Wind turbines are often design to deal with a wide range of conditions. Nevertheless, where wind speeds are expected to increase, design can be adapted to capture more energy and produce more electricity. As well as trying to make infrastructures invulnerable against climate change, adjustments in the operation of the infrastructure help increase the resilience of the entire system. Thus, we can display both engineering and non-engineering adaptation measures of the wind sector.

Engineering measures

- Construct turbines that can operate at, and physically withstand, higher wind speeds, higher wind gusts and direction changes;
- At higher latitudes, changes in permafrost conditions have a great impact in the designing of the foundation of wind turbines. Design a foundation which support all the weight, plus the system frequencies and variable forces exerted by the rotating turbine (Pryor and Barthelmie, 2010);
- Design offshore turbine designs to withstand expected increases in wind-sea wave forces;
- Use taller towers to capture the stronger winds at higher altitudes;
- Consider the development and commercialization of vertical axis wind turbines, which are less sensitive to rapid changes in wind direction. They could potentially yield an order of magnitude increase in wind farm energy output per unit of land area, as vertical axis systems can be place close together without significant turbine wake effects;
- Insure against impact of storms on long-term power yields and damage;
- Consider the effects of extreme low and high temperatures in turbine (and blade) selection and operation, as these can alter physical properties of materials (e.g., rubber seals may become brittle at low temperatures; hydraulic systems and lubricant needs may change);
- Implement passive and active methods to reduce icing. A passive method is the blade design to reduce ice accumulation; an active method is blade heating (Pryor and Barthelmie, 2010);
- Integrate increased amounts of wind energy into the grid, as well as improve grid stability.

Non-engineering measures

- Choose sites for new infrastructures or relocate existing turbines in sites that take into account expected changes in wind speeds during the lifetime of the turbines, as well as sea level rise and changes in river flooding;
- Siting procedure to take into account expected changes in wind speeds during the lifetime of the turbines and to account for anticipated sea-level rise changes in river flooding;
- Ensure the presence of rapid emergency repair teams to repair damaged turbines quickly;
- Develop insurance schemes for long-term wind power yields and damage from storms;
- Develop meteorology-based weather/climate forecasting.

Solar power

Solar energy can be exploited in three different types of production systems: in a solar photovoltaic system (PV), in a Concentrating Solar Power system (CSP) and in a thermal system. All three technologies are likely to be affected principally by the same climate impacts: temperature increases, increased cloud cover and increased extreme events.

Following, there will be an account of the engineering and non-engineering options for the photovoltaic systems, the CSP systems and the thermal systems. Specific adaptation options for PV, CSP and thermal systems will be marked to distinguish them from the adaptation measures which could be applied to the three production systems.

Engineering measures

- Assure that structures are strong enough to withstand higher winds (although roof-mounted structures cannot be more robust than the building on which they are located);
- Specify stronger mounting structure;
- Specify cabling and components that can deal with high moisture content and flooding;
- Specify heat-resistant PV cells and module components designed to withstand short peaks of very high temperature (PV);
- Use designs that improve passive airflow beneath photovoltaic mounting structures, reducing panel temperature and increasing power output (PV);
- Select appropriate tilt panel angle to clean dust;
- Select module surface favorable to self-cleaning;
- In dry areas, consider panel washing system to remove dust and grit;
- Where snowfalls are heavy or likely to increase, assure free space so that snow can slide off the panel;

- Where solar energy is likely to become more diffuse, with changes in cloud cover, rough surfaced photovoltaic modules are more efficient and output can be improved under overcast conditions by selecting an appropriate tilt angle;
- Where clouds are likely to pass over modules more quickly, consider micro-inverters for each panel (in place of small numbers of large centralized inverters) to improve stability and increase power output (PV);
- Consider distributed systems (rather than feeding power into a single part of the grid), which can improve grid stability (although mobile repair teams may be needed to repair damage from extreme events);
- For any tracking solar system for CSP, the motors and their mounting must be especially robust wherever stronger winds and particularly more intense storms and gusts, are expected (CSP);
- Avoid tracking systems where cyclones are expected to increase in strength (CSP);
- Where temperatures are likely to increase, it may be interesting to consider forced air and liquid coolant systems (Patt et al., 2010), (CSP);
- Where water shortages are expected consider air cooling (CSP);
- Use evacuated tube collectors for thermal heating because they do not suffer from ambient temperature problems as much since their inner tube is insulated by a vacuum (Patt et al., 2010), (Thermal);
- Use engineer evacuated tube collectors with higher resistance to hailstorms (Patt et al., 2010), (Thermal);
- Use evacuated tube collectors than flat plate collector when there is more diffuse than direct insolation (it occurs when there is cloudy weather). (Patt et al., 2010), (Thermal).

Non-engineering measures

- Develop meteorology-based weather/climate forecasting;
- Where possible, site solar photovoltaic, CSP and thermal systems where expected change in cloud cover are relatively low, although this is difficult to accurately predict;
- Choose locations with lower probability of dust, grit and snow;
- For locations where temperature increases or significant heat waves are expected, choose modules with more heat-resistant photovoltaic cells and module materials designed to withstand short peaks of very high temperature;
- For distributed solar systems, make available mobile repair teams to ensure functioning of systems after damage from extreme events.

Biomass and biofuels

Adaptation measures for bioenergy systems are similar to those of other high-intensity agriculture. The Food and Agriculture Organization (FAO), for example, has carried out numerous studies on improving climate change resilience in agriculture, as *Climate-Smart Agriculture: Policies, Practices and Financing for Food Security, Adaptation and Mitigation* (Food and Agricultural Organization of the United Nations (FAO), 2010). These are equally applicable to bioenergy and mixed energy/food production systems.

Following, we will differentiate, as usual, the engineering and the non-engineering measures to adapt the system. Moreover, we will list some FAO's options taken from *Climate risk and adaptation in the electric power sector* (Asian Development Bank, 2012) and some other results from the study *The vulnerability of renewable energy to climate change in Brazil* (de Lucena et al., 2009).

Engineering measures

- Expand irrigation systems or improve the efficiency of existing irrigation to counteract drought impact if sufficient water is available from sources outside drought-hit area;
- Use unconventional sources such as desalinated seawater or fossil water resources if there is no availability of conventional water resources;
- Protect against floods by building dykes and improving drainage;
- Expansion of rainwater harvesting, water storage and conservation techniques, water reuse and desalination;
- Improve water harvesting and use;
- Improve soil and nutrient management;
- Increase the robustness of biomass power plants.

Non-engineering measures

- Use of salt-tolerant pants (halophytes) – including varieties of sugarcane, millet and corn that grow in brackish water on saline land – or robust crops with high biological heat tolerance and water stress tolerance than current crops;
- Adjust crop management and rotation schemes;
- Adjust planting and harvesting dates;
- Introduce soil moisture conservation practices as the use of trees and shrubs in agricultural systems to improve soil fertility and moisture though increasing soil organic matter;
- Relocate crops in areas with lower risk of flooding and storms;
- Implement early warning systems for seasonal rainfall and temperature anomalies;
- Support emergency harvesting of biomass in case of an imminent extreme event;
- Provide crop insurance schemes.

As mentioned above, now we give an account of the FAO's and de Lucena's results about the measures to improve agricultural systems.

FAO advocates the merging of adaptation, mitigation and even prevention actions to produce an overall strategy of resilient adaptation for agricultural systems. The conclusions are equally valid for biomass and biofuel energy.

- Improve water harvesting and retention and water-use efficiency for increasing production and address increasing irregularity of rainfall patterns;
- Control pests and diseases because climate change appears to be altering the distribution, incidence and intensity of animal and plants pests and diseases;
- Improve ecosystem management and biodiversity to provide a number of ecosystem services which can lead to more resilient, productive and sustainable systems;
- Use genetic resources to determine tolerance to shocks such as temperature extremes, drought, flooding, pests and diseases. It also regulates the length of the growing season or production cycle and response to inputs as fertilizer, water and feed;
- Implement efficient harvesting and early transformation of agricultural produce to reduce post-harvest losses and preserve crop quantity and quality.

Finally in *The vulnerability of renewable energy to climate change in Brazil* (de Lucena et al., 2009) the authors studied the impacts of global climate change on the geographic distribution of sugarcane and oilseed crops in Brazil. For sugarcane, they found that cultivation will become unfeasible in some regions because of GCC, but other regions could take up the slack by continuing to have a temperature range favorable to sugarcane. Therefore, they suggested shifting geographical distribution. The same considerations could be made for the various species of oilseed pants grown in the country.

Wave and tidal energy

Energy from the ocean – sea wave, tidal and the extremely complex and unproven ocean thermal energy conversion (OTEC) – is primarily exploratory in nature and not yet commercialized. Energy from tidal flows can be considered commercial, but is a niche hydropower technology with limited practical application. However, there is considerable development of sea wave technologies (in UK), some of which can be considered near commercial and tidal energy is under construction in Asia.

Adaptation measures to improve the resilience of sea wave, tidal and OTEC systems to climate change can be divided, as usual, into engineering and non-engineering options. Some actions are taken from the document *The potential of wave energy* (Hayward and Osman, 2011).

Engineering measures

- Devices need to be engineered to withstand extreme waves, by being massive or alternatively inexpensive enough that the financial loss is no too great;

- For sea wave floating systems, consider designing for 50-year freak waves (with an amplitude about 10 times the average wave with 100 times the wave energy);
- For sea wave anchorage systems, design them to be oriented in the wave direction rather than across the wave front to reduce vulnerability to severe stresses;
- Consider protection mechanism against storm surges such as automated lowering of expensive components to the sea floor; design devices which cope sufficiently seaworthy; disconnect or shut down devices so they are not operating during extreme events;
- Raise level of barrage basin walls for tidal systems;
- For OTEC, construct larger pipes to increase volume of water to the surface;
- Design deep-sea pipes to withstand greater stresses.

Non-engineering measures

There is only one non-engineering measure that is relative to wave energy systems. The measure is to consider onshore or nearshore systems to produce electricity, because they are less vulnerable to storm damage, although the power available is less than further out at sea.

Thermoelectric power plants (thermal cycle efficiency, cooling system, infrastructures)

In this thesis thermoelectric power plants are all those plants which use a steam cycle (Rankine cycle) or a turbine (Brayton-Joule cycle) to produce electricity from an energy resource. Therefore, in this category we include: the normally-called thermal power plants, which use as fuel coal, oil and gas; nuclear power plants that use a steam cycle to produce energy and geothermal power plants. All these power stations present a thermal cycle, a cooling system and infrastructures, which are all vulnerable to climate change. Thus, they all should be adapted with engineering and non-engineering measures.

Power stations and related infrastructures can operate for 50 years or more (nuclear plants for 100 years). Therefore, adaptation measures should consider a range of projections including gradual change and not only more rapid changes and additionally possible changes in extreme events over the period. The various measures for the various components and the various kinds of structures may be different but also may be very similar if not identical. In this way, we will distinguish the engineering from the non-engineering options, but we will not divide the measures for the different components and the different plants.

Engineering measures

- Develop and implement higher structural standards for new or renovated buildings;
- Build concrete-sides buildings instead of metal because they are more resistant to wind and corrosion;
- Raise level of structures;

- Develop flood control where floods are likely to increase. Implement embankments, dams, dykes, reservoirs, polders, ponds, relocated flood defense, barriers and higher channel capacity;
- Construct improved coastal defenses (seawalls and bulkheads);
- Improve drainage and reroute water pipes;
- Protect fuel storage including stockpiles;
- Change the cooling system from a once-through to a closed-circuit, withdrawing less water from source (Linnerud et al., 2011);
- Redesign cooling facilities: recover water from condense and heat exchangers, reduce evaporative losses, increase secondary or wastewater usage, construct dry cooling towers;
- Increase volume of water treatment works and develop new water sources;
- Install additional cooling towers and modify cooling water inlets at coastal locations;
- If cooling water is unavailable with climate change, air-cooled systems could be used;
- Use dry or hybrid cooling systems with lower water requirements;
- Develop more efficient pumps and heat exchangers.

Non-engineering measures

- Choose better locations (less exposed places) to build new thermal plants (Linnerud et al., 2011);
- Concentrate investment in locations where temperatures are likely to be cooler;
- Decentralize generation;
- Invest in more cooling capacity and in different cooling technologies (Linnerud et al., 2011);
- Invest in more spare production capacity and more network capacity (Linnerud et al., 2011);
- Require more stringent safety investments;
- Develop and implement higher structural standards for new or renovated buildings;
- Incorporate gradual sea level rise, increased storms events and associated tidal surges into design criteria;
- Formulate long-term strategies to respond to climate-related disruption;
- Restore/afforest/reforest land.

Fossil fuel extraction, production and refining

For fossil fuel extraction and production we mean the extraction of coal and production of oil and gas. The facilities, the mines and the oil and gas fields are vulnerable to climate changes and they will need some engineering and non-engineering adaptation measures.

Engineering measures

- Build or enlarge reservoirs of water to reduce flooding risk in new and existing mining developments;
- Reassess flood-prone areas and elevating buildings or vulnerable components above the 100-year food contour level;
- Build flood-proofing buildings;
- Power plants and pumps should preferably be sited where there is an adequate supply of cooling water. Air cooling should be considered as an alternative to water cooling;
- Build or improve onshore dykes, berms and spillways;
- Build or enlarge reservoirs of water to reduce water shortages;
- Develop or reroute water source;
- Improve the robustness of designs, particularly offshore installation that are vulnerable to storms.

Non-engineering measures

- Site future mines in areas that have a limited exposure to flooding or drought risk;
- Adopt techniques that slow, steer and block water flows;
- Carry out flood hazard assessments;
- Improve models used to predict storms

Transmission, distribution and transfer of energy

Transmission and distribution of energy refers essentially to the electricity grid system, whereas transfer of energy refers to the transportation of fuel fossils. Therefore, the adaptation measures regarding these two kinds of energy transfer are different.

The measures for fuel transfer could be summarize in few words. The transfer of oil could be increased making more robust and structurally flexible the pipeline designs and increasing the reliability of the nodes of the pipelines (the valves and the pumping stations). The transportation of other fossil fuels by rail, boats, barges and trucks are principally vulnerable to floods: the adapting measure is fundamentally increase the protection against flooding.

Improving the resiliency of electricity infrastructure, instead, involves preparing the transmission and distribution (T&D) systems to continue operating despite damage. Adaptation efforts should increase the system's ability to return to normal operations rapidly if outages do occur. Specific options could always be divided into engineering and non-engineering measures.

Engineering measures

- Reinforce existing T&D structures and build underground distribution systems;
- Where stronger winds are expected, strengthen distribution poles with guy wires;

- Where lightning strikes may increase, include lightning protection (earth wires, spark gaps) in the distribution network;
- Where higher temperatures may occur, specify more effective cooling for substations and transformers, including retrofitting measures, improved shading and choice of cooler locations where possible;
- Design improved flood protection measures for the infrastructure and for the equipment mounted at ground level in substations;
- Protect poles, antennae, switch boxes, aerials, overhead wires and cables from precipitation, wind, unstable ground conditions and changes in humidity;
- Build a resilient high-capacity transmission system;
- Change routes of overhead lines along roads away from trees and use covered and/or insulated conductors and more underground cables especially in wooden areas;
- Use smart transformers which control the flow of electricity to stabilize existing aging power grids;
- Develop and use smart grids;
- Design more flexibility into T&D networks, allowing increased rerouting during times of disruption;
- Reduce pressure on the grid through distributed, decentralized energy generation, although care must be taken to maintain grid stability.

Non-engineering measures

- Require higher design standards for distribution poles (usually wood) and towers (steel);
- Specify more effective cooling for substations and transformers;
- Invest resources into building a resilient, high-capacity transmission system;
- Improve system management through investing in smart grids;
- Forbid the construction of power lines near dikes and ban permanent trees next to existing dykes;
- Specify Information and Communication Technology (ICT) components that are certified as resilient to higher temperatures and humidity. Design improved redundancy into ICT systems, including wireless transmission better able to handle high temperatures.

6.1.3.3 The adaptation management

In this part, we deal with those ways to adapt energy systems to climate change that are not closely related to a system vulnerability, as the demand side and supply side measures. Here we treat, among other things, the sharing of responsibility, the exploitation of opportunities and the integration of planning.

Sharing responsibility

Adapting energy systems with measures to consequences of climate change prevents losses and risks. This is not the only way to adapt the energy system. The energy sector can share responsibilities for losses and risks by hedging weather events or diversifying the energy mix.

In finance, a hedge is a position established in one market to attempt to offset exposure to price fluctuations in some opposite position in another market, with the goal of minimizing one's exposure to unwanted risk. Specifically, the weather risk market makes possible to manage the financial impact of weather through risk transfer instruments based on a defined weather element, such as temperature, rain, snow, wind and so on. Weather risk management is a way for organizations and individuals to limit their financial exposure to disruptive weather events.

Energy is a sector whose operations and profits can be significantly affected by weather: unexpected weather events can cause significant financial losses. The use of financial instruments, such as weather derivatives and insurance, provides a means to clients to protect themselves against adverse financial effects due to variation in weather and climate.

Exploiting opportunities

Sometimes adaptation can result in a win-win outcome: in this case, adaptation provides the reduction of the impact of climate change and the improvement of some other dimension of our well-being.

An example of this kind of measure is the energy/water saving with demand-side management. These measures provide a cost-effective win-win solution for mitigation and adaptation concerns, in a context of rising demand and supply constraints.

Another example is to decentralize energy. It would reduce the probability of suffering large-scale outages when centralized power systems are compromised. It would base on locally available renewable energy sources situated in secure locations.

More than a half of the world's population now lives in cities: these cities are important and growing consumers of energy. Thus, urban policy and land-use planning will play an important role in improving the resilience of the energy system.

Integrated planning

Adaptation action may be required for an entire energy system or may involve interactions between different segments of the energy sector or other sectors, such as water or agriculture. Adaptation may involve not only different sectors, but also different agents. This happens because there are many indirect impacts of climate change in the energy sector, as well as indirect impacts on other economic sectors through impacts on energy.

Integrated planning within energy sector and others such as water sector is therefore highly important. Energy and water systems are closely linked. The production/consumption of one resource can not be achieved without making use of the other. In addition, climate change affects the supply of both resources. Therefore, policy makers cannot provide a good adaptation plan without integrating both sectors as parts of a single strategy.

Integrated assessment tools can be used to evaluate different adaptation options. The main advantage of an integrated assessment is that it allows the examination of the adopting of a set of adaptation measures.

When integrating climate risks into new investments, planners need to deal with the uncertainty related to climate scenarios. There is also a great deal of uncertainty about the evolution of technical and economic parameters used in the analysis, that further adds to the already high level of uncertainty of climate impact assessments. Usually uncertainty is taken into account by using scenarios where the model assumes perfect foresight. In reality, decision makers do not have full information about the technical and economic characteristics of the technologies and the constraints that energy system will face in the future.

The Water-Energy-Food Nexus

Water, energy and food are linked through numerous interactive pathways affected by the changing climate. The depth and intensity of those linkages vary enormously among countries, regions and production systems. Many energy sources require significant amounts of water and produce a large quantity of wastewater, that requires energy for treatment. Food production, refrigeration, transport and processing also require both energy and water. A major link between food and energy, as related to climate change, is the competition of bioenergy and food production for land and water. In addition, there is a link also trough the sensitivity of precipitation, temperature and crop yields to climate change.

The consideration of the interlinkages of energy, food, water, land use and climate change has implications for security of supplies of energy, food and water, adaptation and mitigation pathways, air pollution reduction and health and economic impacts. This nexus is increasingly recognized as critical to effective climate-resilient-pathway decision making.

Talking about biomass for energy and sustainability, to offset competition between energy and non-energy crops, it is important to invest in more efficient energy and fuel conversion techniques to improve energy availability. This means to increase crop productivity, increase energy production per unit of biomass consumed and assure sufficient biomass supplies to convert into energy. Crop management practices such as irrigation, mechanized harvesting and development of new species through genetic improvements are good examples of practices that may work in favor of land productivity.

Adaptation in sectors as agriculture, forestry and industry might have impacts on the freshwater system: therefore, it needs to be considered while planning adaptation in the water sector. For example, better agriculture land management practices can reduce erosion and sedimentation in river channels, while controlled flooding of agriculture land can alleviate the impacts of urban flooding. Increased irrigation upstream may limit water availability downstream. (IPCC, 2014, p.257).

The integration of energy and water resource management is also important. Worldwide water demand is expected to grow due to increasing population and affluence. Climate change may have some effects on freshwater systems that can aggravate the impacts caused by other stresses, such population growth, land use and urbanization. Thus, current water management practices may not be able to deal with these impacts, particularly due to the traditional assumption that past hydrological experience provides a good guide to future conditions.

From an energy perspective, competition for water can create stress in a dryer climate due to the high water demand for power generation (hydroelectricity, thermal power and nuclear energy). The availability of water will have regional implications and directly affect the planning and siting of new capacity and the development of new technologies. Water resource management will therefore become an increasingly important tool for solving conflicts and optimizing the use of natural resources for energy and other uses.

When it comes to thermal power plants, improvements in cooling system technologies are crucial for water management. Recirculating cooling systems are less vulnerable to modifications in water availability than once-through cooling systems, as the amount of water required in the former is smaller than in the latter.

The combination between these three sectors is very significant. Some adaptation solutions or strategies in one or two areas could affect positively the others. An example of this correlation could be the implementation of Sustainable Urban Drainage Systems (SuDS) for food production (Girardi et al., 2014). The main targets of this strategy is to increase food production in urban areas and reduce dependency on the countryside and food imports, improving the recovery and management of water in cities. In this way, SuDS can reduce the likelihood of floods in areas at risk. The application of this strategy could bring benefits for climate change adaptation. The most evident effect will be the reduction of water use and the risk of floods. But as a result, these effects could bring other benefits in other sectors like the energy one, which is also affected by water scarcity and flood risk. A project designed for other purposes, which might not be energetic and might not focus on adaptation, may also deliver an increased resilience to climate change as a co-benefit, even without a specifically identified adaptive component.

Other actions to support adaptation

As we know, the energy supply chain is vulnerable to the consequences of global warming. To date, decision makers have focused on maximizing energy supply to satisfy industrial and societal demand for energy, while they managed the risks perceived to be of immediate concern and not to be faraway. All available evidence suggests that managing the risks posed by current and future climate is not an optional add-on but a necessary management and planning concern, that is likely to become increasingly important as the consequences of climate change materialize.

Adaptation is an expansive area, which covers many sectors and socioeconomic structures. Adaptation to the impacts to this area is likely to involve a drawn out process that requires major investments and strategic decisions. The World Bank in its study *Climate impacts on energy systems: key issues for energy sector adaptation* (Ebinger and World Bank, 2011) stressed some other actions in the short term to help mainstream climate considerations into energy sector planning and management. Some options have already been underlined during the thesis, especially talking about climate resilience.

- **Undertake climate impacts needs assessment**
  Location specific adaptation requirements are dependent on an analysis of impacts. Climate impact analysis is the first step toward the development of adaptation strategies. Such an assessment should quantify the impacts and hence risks, giving data through the energy life cycle to guide adaptation practice in any country. It should incorporate and critique existing practices and potentially include an assessment of the associated costs of impacts.
- **Develop project screening tools**
  Develop templates to screen individual energy projects for climate vulnerability and risks. Develop supporting guidance, information and simple decision rules for climate risk integration into decision-making. Simulation modeling could support the development of pertinent "what-if" scenarios.
- **Develop adaptation standards for the energy sector**
  Such standards should cover engineering matters and information requirements. Though the development of standards is beyond the responsibilities of the UNFCCC, it could be handled through the energy sector itself, through international organizations such as the UN, International Energy Agency (IEA), International Renewable Energy Association (IRENA) and universities or research institutions. Some examples include: standards for robust coastal infrastructure that take into account the anticipated strength of extreme weather events; revised zoning standards to minimize climate risks for future assets; construction standards in traditional permafrost areas to accommodate changes in soil structural characteristics.
- **Revisit planning timeframes and the use of historic data for future investments**
  Traditional planning approaches that use historic data may need to be revisited and

adjusted to reflect anticipated climate trends. There is a need to review and implement changes in the use of historic data as a basis for future energy investments.

6.2 The adaptation agents

To address adaptation appropriately in the energy sector it is necessary to consider the perspectives of both the public and private sides. As recognized by the International Finance Corporation (IFC):

> "*The private sector is expected to finance most of the measures required to mitigate greenhouse gas emissions and adapt to the effects of climate change.*" (Ebinger and World Bank, 2011, p.69)

Private adaptation is the adaptation initiated and implemented by individuals, households or private companies: it is usually in the actor's rational self-interest. Instead, public adaptation is initiated and implemented by government at all levels and it is usually directed at collective needs. The rational self-interest of the private sector normally extends into public-private partnerships and other agreements. There is the danger that adaptation costs, often allocated with greater proportion at the beginning of the project, may be neglected by the private and perhaps the public sector. This danger exists unless commitment length of a project is sufficient to incorporate discounting of adaptation costs and unless awareness of the adaptation issue is adequate.

Enabling government policies are a key aspect of ensuring effective public-private links, including attention to adaptation, in all countries. However, even with the best government policies, financial rewards will always remain the prime motivator for investments.

Energy regulators help manage the many positive and negative externalities facing the energy sector. Regulation can additionally support competition in transport networks and encourage risk management. Private economic agents (producers and consumers) benefit from energy security and reliability but do not pay for them in the absence of regulation and/or economic incentives.

Global climate change may increase the need for regulation because:

- Climate impacts and risks to energy security are expected to increase in the long-term;
- Climate change may reduce energy security and reliability;
- Decision uncertainty will rise with the higher frequency and intensity of extreme events;
- Private investors will be faced with increased uncertainty on long-term investments;

- Climate policies that provide incentives for renewable energy generation and trading may affect energy transmission and market frameworks.

Energy regulators will need to improve resilience in an increasingly uncertain environment. Regulators will also need appropriate climate information to support policy development. Thus, in the context of climate change, regulatory action could include:

- Economic incentives and mandatory regulation to increase investment in flexible energy supply facilities to ensure a quick response to supply-side losses linked to extreme weather events;
- Incentives for utility-led demand-side management programs;
- Rules for prioritizing energy cuts during extreme weather events;
- An auction system for consumers to allow them to bid for reduction in energy consumption during supply shortages;
- Research on advanced systems for electro-mechanical energy storage;
- Emergency biofuel stocks for supply interruptions during extreme weather events and to manage seasonal supply variations. Emergency stocks can be regarded as a public good, providing external benefits to private agents;
- Reduce information gaps. Energy system information should be regarded as a public good.

In any case and for any plan, there is a basic operation which must be implemented to support in the best way adaptation and the support decision making. This measure is the investment in observations and in weather and climate services. Information gaps could be filled in collaboration with existing international organizations and programs, such as the WMO, the Global Climate Observing System and the Global Framework for Climate Services. National hydro-meteorological service centers may not have the resources to fulfill all energy sector observational requirements. Although these climate observation networks are expensive to develop and maintain, they can provide essential inputs into planning for climate change. Some options to improve the quality and flow of such information to the energy sector could be to improve observation networks, support data rescue and archiving, upgrade resources for weather and seasonal forecasts and outlooks, build capacity to prepare projections of climate and associated impacts and support cross-sector dialogue.

PART D

CASE STUDY: ADAPTING SPANISH AND ITALIAN ENERGY SYSTEMS

CHAPTER 7

THE SPANISH AND ITALIAN ENERGY SYSTEMS

Part D, the final one of the thesis, supports the understanding of the entire work of the investigation. It puts into practices the method of analysis of a generic energy system elaborated during the entire composition. Besides, the examined case study is one of the primary purposes of the research.

This case study discusses the adaptation of two specific electricity systems to climate change, the Spanish and Italian ones. It concentrates on the three main parts that constitute the entire investigation, but it follows a different outline. The framework of the case study will be a little different. The study will start with the analysis of the Spanish and Italian energy systems and not with the analysis of climate changes and climate impacts in the countries. Examining the systems before the changes and impacts, permits us to know which climate changes and climate impacts we have to focus on more. The second part of the case study consequently treats climate change and climate change's impacts on energy systems. Finally, the last part explores the adaptation measures of the energy systems.

Chapter 7, the first section of the case study, will be mainly focused on the description of the Spanish and Italian energy systems, paying special attention on the electricity systems. This characterization is useful to identify the vulnerabilities of the systems related to the projected climate change.

In chapter 8 we will analyze the climate variability and future climate change in Spain and Italy. Then, we will describe the major impacts of climate change on natural system and the events which could affect the energy systems of the two countries. The basis of this analysis will be the diagram of the path of climate change introduced in Chapter 2. We will not examine in depth the climate impacts and their values, but we will only discuss their tendencies and trends. A most specific investigation will be made in Chapter 9.

Finally, chapter 9 will summarize the adaptation measures and further the other parts of the study. We will include specific summary tables to recap the vulnerabilities of the energy systems, the projected impacts of climate change in the two countries and the possible adaptation options.

Specifically, Chapter 7 will focus on the energy systems of the two examined countries. We will start with an account of the overall energy balance of each country and with some historic data about the production and the demand. Then, we will analyze specially the electrical energy balance of the countries, putting greater attention on the installed capacity and the electricity production. Finally, we will delineate the transmission and distribution grids.

7.1 The Spanish energy system

7.1.1 The Spanish overall energy balance

An overall energy balance is an accounting of all energy which enters, exits and is used within the national territory of a given country during a reference period. The energy balance expresses all forms of energy in a common accounting unit (thousand ton of oil equivalent, ktoe), and shows the relationship between the inputs to and the outputs from the energy transformation industries.

In table 7.1 we can see an example of energy balance for the Spanish system edited by the International Energy Agency (“IEA - Report Energy Balance,” n.d.). In this balance we can find data about the supply of energy, the resources used for electricity production and the total final consumption for the country.

Table 7.1 2013 Spanish Energy Balance in thousand tonnes of oil equivalent (ktoe) on a net calorific values basis, based on 2013 Balances of IEA (“IEA - Report Energy Balance,” n.d.)

2013	COAL	OIL[1]	NATURAL GAS	NUCLEAR	RENEWABLE[2]	ELECTRICITY	TOTAL
PRODUCTION	1763	375	50	14784	17523	0	34496
IMPORTS	8076	78843	30868	0	777	850	119414
EXPORTS	-506	-21814	-5073	0	-713	-1431	-29537
BUNKERS[3]	0	-10744	0	0	0	0	-10744
STOCK CHANGES	1673	1146	311	0	-32	0	3099
TPES[4]	11007	47806	26155	14784	17555	-581	116727
CONSUMPTION IN PLANTS[5]	-9362	-2753	-8752	0	-521	-3485	-23375
OTHER CONSUMPTION[6]	-570	-5168	-2150	-14784	-11742	24018	-11896
TOTAL FINAL CONSUMPTION	1075	39884	15252	0	5292	19953	81457
INDUSTRY	938	2671	9033	0	1457	6018	20118
TRANSPORT	0	26760	120	0	898	370	28147
CIVIL[7]	96	4027	4689	0	2848	12898	24557
PRIMARY SECTOR[8]	41	1878	940	0	89	667	3616
NON-ENERGY USE	0	4549	470	0	0	0	5019

Note. (1) includes crude oil and oil products. (2) includes hydro, geothermal, solar, biofuels, waste, etc. (3) includes international marine and aviation bunkers. (4) means Total Primary Energy Supply. (5) considers the consumption in plants to generate electricity. (6) considers consumptions in other facilities and sectors, like oil refineries, coal transformation, liquefication plants, etc. (7) includes residential, commercial and public services consumptions. (8) includes the consumptions in agriculture, forestry and fishing.

7.1.2 The Spanish energy context

According to the *Observatorio de Energía y Sostenibilidad en España. Informe basado en indicadores. Edición 2014* (Catedra BP de Energía y Sostenibilidad, 2015), the Spanish energy sector consumed 5.93 EJ of primary energy in 2013.

Tables 7.2 and 7.3, and Figure 7.1 from the report *La energía en España 2013* (Secretaría de Estado de Energía, 2014) represent the final energy consumption and the primary energy consumption in ktoe in Spain in 2012 and 2013, with the relative rates of change.

Table 7.2 Final energy consumption (ktoe) (Secretaría de Estado de Energía, 2014, p.35)

	2012	**2013**	**RATE OF CHANGE %**
	ENERGY USE		
COAL	1233	1369	11.0
GASES DERIVED FROM COAL	274	263	-3.8
OIL PRODUCTS	39917	39061	-2.1
NATURAL GAS	14632	14653	0.1
ELECTRICITY	20661	19952	-3.4
RENEWABLE ENERGIES	6273	5329	-15.0
TOTAL ENERGY USE	82990	80627	-2.8
	NON-ENERGY USE		
OIL PRODUCTS	5626	4358	-22.5
NATURAL GAS	355	451	27.0
TOTAL FINAL USE	88971	85436	-4.0

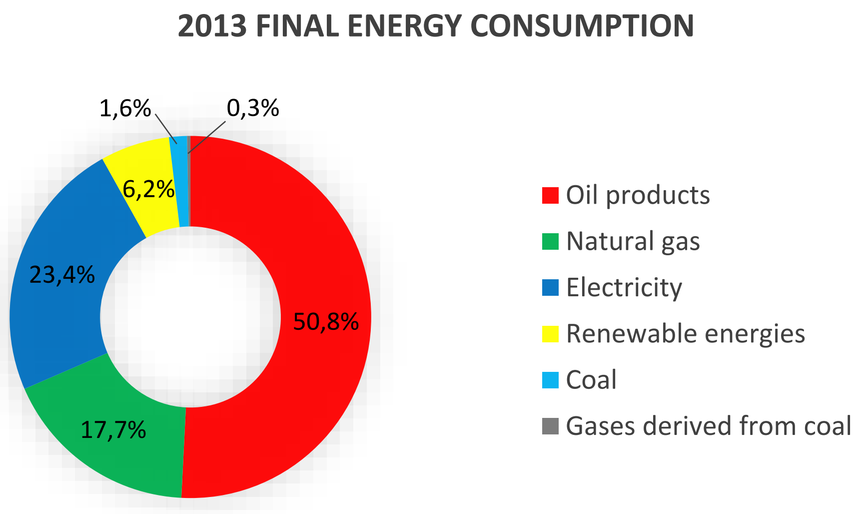

Figure 7.1 2013 Spanish final energy consumption (Secretaría de Estado de Energía, 2014, p.36)

Table 7.3 Primary energy consumption (ktoe) (Secretaría de Estado de Energía, 2014, p.36)

	2012	**2013**	**RATE OF CHANGE (%)**
COAL	15510	10531	-32.1
OIL	53978	52934	-1.9
NATURAL GAS	28184	26077	-7.5
NUCLEAR	16019	14785	-7.7
HYDROPOWER	1767	3163	79.0
WIND, SOLAR, GEOTHERMAL	6679	7665	14.8
BIOMASS AND BIOFUELS	7558	6383	-15.5
NON-RENEWABLE WASTE	176	160	-9.1
ELECTRICITY IMPORT-EXPORT	-963	-579	-39.9
TOTAL	128908	12119	-6.0

By dividing the final and primary energy consumption for the gross domestic product, we obtain the value of energy intensity (Table 7.4 from *La energía en España 2013*). The final and primary energy intensities and their relative annual changes are useful indicators to quantify some peculiarities. For example, the improvement of the primary intensity in 2013 was higher than the improvement of final intensity: this diversity must be sought in the fact that the structure of electricity generation changed and the general generation efficiency increased.

Table 7.4 Final and primary energy intensities (Secretaría de Estado de Energía, 2014, p. 37 and p.38)

	FINAL EN/GDP toe/million €2005	**FINAL EN/GDP annual change (%)**	**PRIMARY EN/GDP toe/million €2005**	**PRIMARY EN/GDP annual change (%)**
2000	114.8	1.6	160.9	-0.2
2001	116.0	1.1	159.1	-1.1
2002	114.4	-1.4	159.3	0.2
2003	117.1	2.3	159.9	0.4
2004	117.6	0.5	162.1	1.3
2005	116.6	-0.9	159.5	-1.6
2006	109.2	-6.3	153.1	-4.0
2007	108.2	-0.9	150.6	-1.7
2008	103.4	-4.4	143.9	-4.4
2009	99.7	-3.6	137.0	-4.8
2010	101.2	1.5	137.1	0.1
2011	98.3	-3.0	136.4	-0.6
2012	95.3	-3.0	138.1	1.3
2013	92.6	-2.8	131.3	-4.9

Note. Energy use and non-energy use are included In the final energy intensity

In Figure 7.2 we can appreciate the evolution of the consumption of primary energy by different sources.

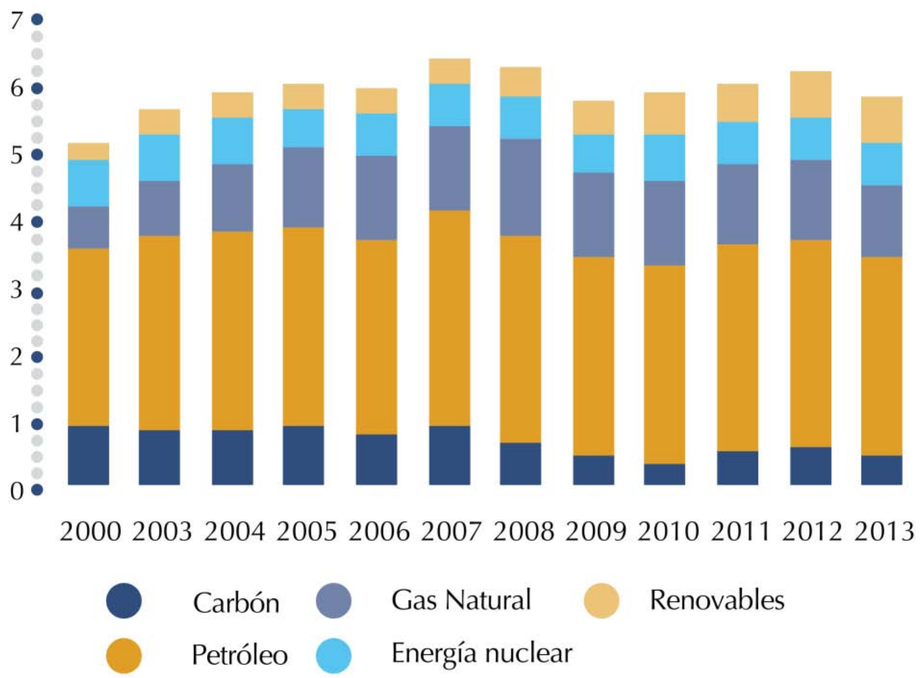

Figure 7.2 Primary energy consumption in Spain (EJ) (Catedra BP de Energía y Sostenibilidad, 2015, p.16)

In 2013 oil consumption accounted for 51% of total primary energy consumption, following by natural gas, whose share has been increasing since 2000 to reach 22% between 2008 and 2010, reaching now 18% of the energy mix. Most of the growth of energy consumption was absorbed by natural gas, as part of the reduction of coal consumption, which has decreased its share since 2000 from 17% to 7.7%. Coal consumption rebounded between 2010 and 2012, then returned to the 2009 level in 2013. Nuclear energy accounted for 10% of consumption in 2013.

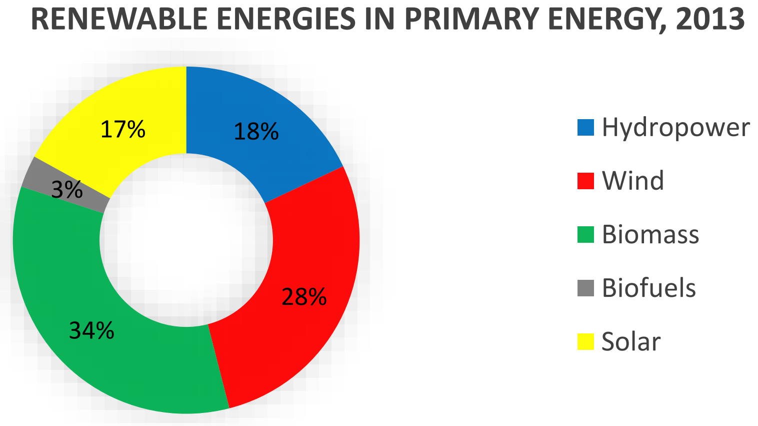

Figure 7.3 Composition of renewable energies in primary energy in Spain in 2013 (Catedra BP de Energía y Sostenibilidad, 2015, p.16)

Renewable energies have experienced a sharp increase of its contribution from 5.6% in 2000 to 12.3% in 2013. Their increase helps natural gas to reduce the historic share of coal in the Spanish energy mix. The share of each renewable resource in the total amount of renewable primary energy remains similar to previous years. The pie chart of Figure 7.3 shows the composition. Biomass is the principal renewable energy source (34%), followed by wind (28%) and hydro (18%). Hydro is followed by solar energy (17%) and then by biofuels (3%). Then the contribution of renewables sources to electricity production grew from 30.5% in 2012 to 41.1% in 2013.

7.1.3 The Spanish electrical system

7.1.3.1 Electrical energy balance

As for the energy system as a whole, it is possible to draw up a specific energy balance for the electricity system. In the IEA website ("IEA - Report Electricity Balance," n.d.) we could find the statistics about the Spanish electricity sector about the year 2013, reported in Table 7.5.

Table 7.5 2013 Spanish Electrical Energy Balance ("IEA - Report Electricity Balance," n.d.)

PRODUCTION	ELECTRICITY [GWh]
COAL	42425
OIL	13763
GAS	57094
BIOFUELS	4697
WASTE	1190
NUCLEAR	56731
HYDRO[1]	41071
GEOTHERMAL	0
SOLAR PV	8297
SOLAT THERMAL	4395
WIND	53903
TIDE	0
TOTAL GENERATION	**283566**

CONSUMPTION	ELECTRICITY [GWh]
IMPORTS	9887
EXPORTS	-16638
DOMESTIC SUPPLY	**276815**
STATISCAL DIFFERENCES	338
EN INDUSTRY OWN USE[2]	**20126**
LOSSES	25018
FINAL CONSUMPTION	**232009**
INDUSTRY	69981
TRANSPORT	4302
RESIDENTIAL	72513
PUBLIC SERVICES	77461
AGRICULTURE/FORESTRY	3867
OTHER NON-SPECIFIED	3885

Note. (1) includes production from pumped storage plants. (2) energy industry own use also includes own use by plant and electricity used for pumped storage

Analyzing the electricity energy balance, we could observe that Spain produced more electricity than its requirements: the balance between electricity imports and exports was negative (-6751 GWh). This fact indicates that Spain on that year was an electricity exporting country (generally it is always true). The data provided by the IEA about electricity production referred to the gross electricity production: the net electricity production is deduced by the energy industry own use (20126 GWh). The losses in the electricity grid settled on 25018 GWh, so the final consumption on 232009 GWh. Commercial and public services, residential and industry sectors consumed almost the all amount of the produced electricity.

In the annual review of the Spanish electricity system composed by Red Eléctrica de España (2015a), we can find a lot of useful data about the Spanish electricity system. First, there are more accurate information about the supply of electricity by different sources, updated to 2014 and reported in Table 7.6.

Table 7.6 2014 Spanish Electrical Energy Balance (Red Eléctrica de España, 2015ª, p.111)

PRODUCTION	ELECTRICITY [GWh]	PRODUCTION	ELECTRICITY [GWh]
HYDROPOWER	35860	SOLAR PV	8199
NUCLEAR	57376	CSP	4959
COAL	46480	THERMAL RENEWABLE	4729
OIL/GAS	6663	COGENERATION	25887
COMBINED CYCLE	25919	**NET GENERATION**	**266853**
CONSUMPTION IN GEN[1]	-7317	PUMPING	-5330
HYDRO-WIND	1	BALANCE IMP/EXP	-3406
OTHER HYDRO	7071	**DEMAND[2] 2014**	**258117**
WIND	51026	**DEMAND[2] 2013**	**261077**

Note. (1) Consumption corresponding to hydraulic, nuclear, coal, oil/gas and combined cycle generation. (2) Demand at bus-bars (see footnote)

Then, in the *El sistema elcectrico español 2014. Síntesis* (Red Eléctrica de España, 2015b) it is reported the evolution of electric energy demand at bus-bars[1] (Figure 7.4), with the relative values of the last five years (Table 7.7).

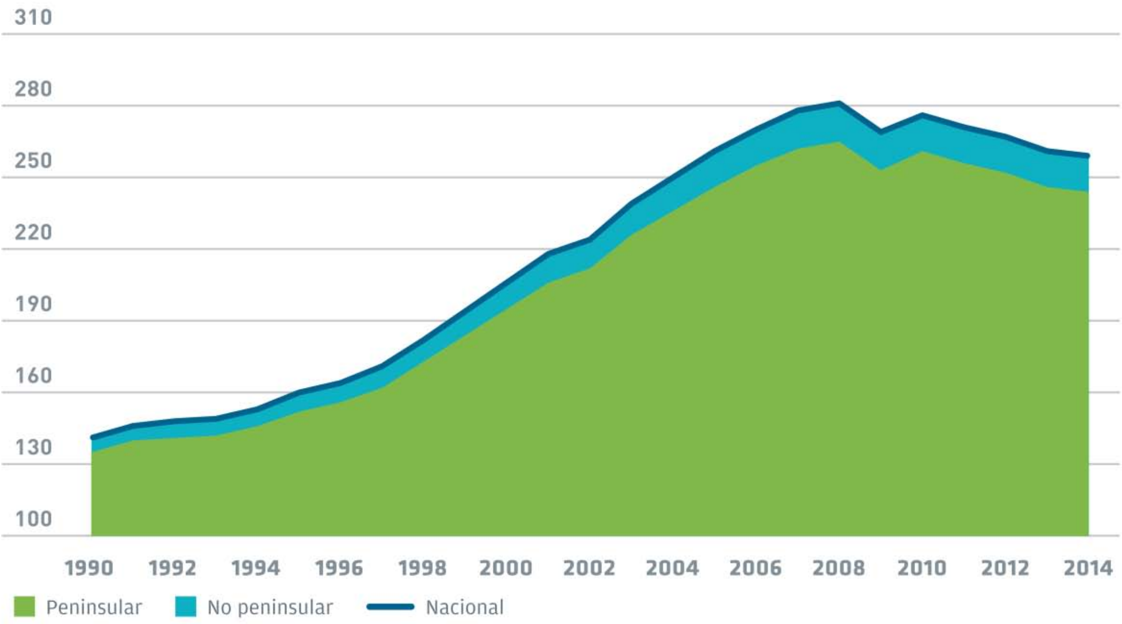

Figure 7.4 The evolution of electric energy demand at bus-bars in TWh (Red Eléctrica de España, 2015b, p.6)

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[1] The bus-bars demand is the energy produced by energy plants net of pumping consumption and exports. To know the final energy use we should detract the transmission and distribution grids losses.

Table 7.7 Annual evolution of electric energy demand in the Peninsula and in the non-peninsular systems (Red Eléctrica de España, 2015b, p.7)

	PENINSULAR		BALEARICS		CANARIES		CEUTA		MELILLA	
	GWh	Δ (%)	GWh	Δ (%)	GWh	Δ (%)	GWh	Δ (%)	GWh	Δ (%)
2010	260527	3.1	5840	-2.5	8895	-2.3	218	2.8	213	3.6
2011	255597	-1.9	5743	-1.7	8870	-0.3	203	-6.7	215	0.7
2012	2552014	-1.4	5823	1.4	8893	0.3	212	4.5	217	1.1
2013	246368	-2.2	5674	-2.6	8624	-3.0	202	-4.8	210	-3.5
2014	243530	-1.2	5585	-1.6	8580	-0.5	212	5.1	210	0.1

7.1.3.2 The coverage of the demand

The pie chart of Figure 7.5 shows the distribution of the installed capacity in Spain at 31 December 2014. We can observe that there is not a dominant technology: the diversification in electricity generation is remarkable. This diversification can be very useful for the adaptation issue because it allows flexibility to meet the demand. The pie chart of Figure 7.6 instead displays how each technology helped to cover the total energy demand in 2014. From this diagram we can note a peculiarity: the electricity contribution of combined cycles is very scarce compared to their installed capacity. Between 2006 and 2010 the installed capacity of combined cycles grow by 63%[2] (data obtained from the REE reports of Spanish electrical system from 2006 to 2010). The combined cycles' generation has decreased every year from 2009 to 2014: the values are very far from the rates of growth that this technology had during their first years of life.

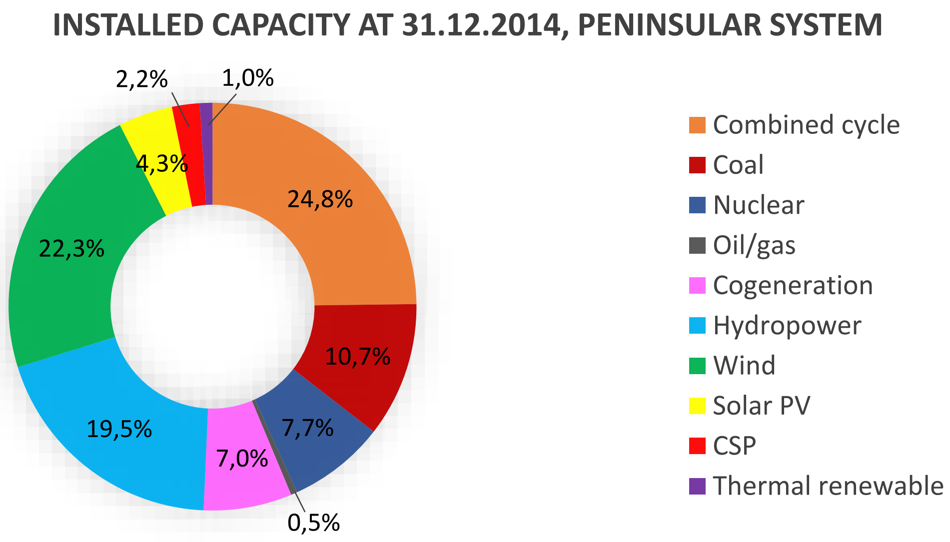

Figure 7.5 Installed capacity at 31.12.2014 in the Spanish peninsular electrical system. Hydropower includes pumping (2517 MW). (Red Eléctrica de España, 2015a, p.11)

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[2] This percentage is calculated from the values of the installed capacity of combined cycles which are expressed in the REE Reports of the Spanish electrical system from 2006 to 2010.

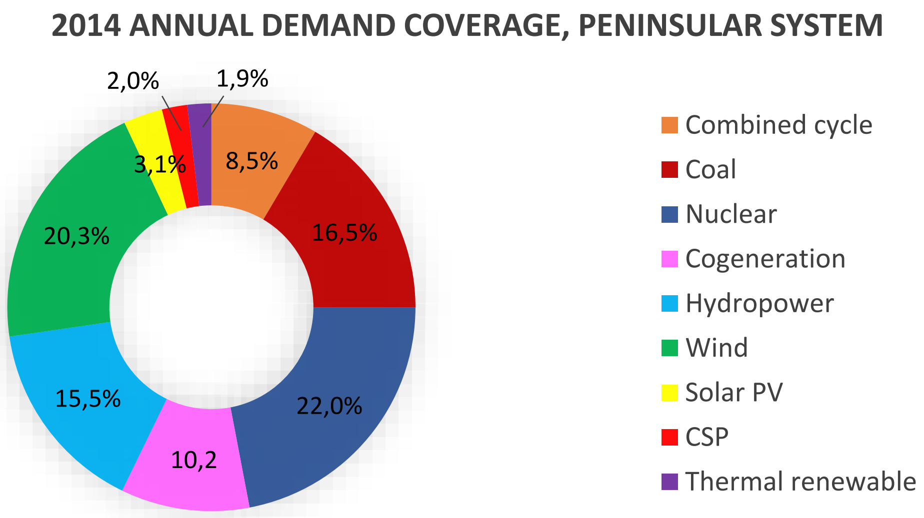

Figure 7.6 2014 annual demand coverage in the Spanish peninsular electrical system. Hydropower does not include pumping (Red Eléctrica de España, 2015a, p.11)

The bar charts of Figure 7.7 report the peninsular installed capacity and peninsular net electricity production of the last 5 years (Red Eléctrica de España, 2015b, p.8). Observing these diagrams, we could catch the evolution of the Spanish electrical system, especially regarding the energy generation.

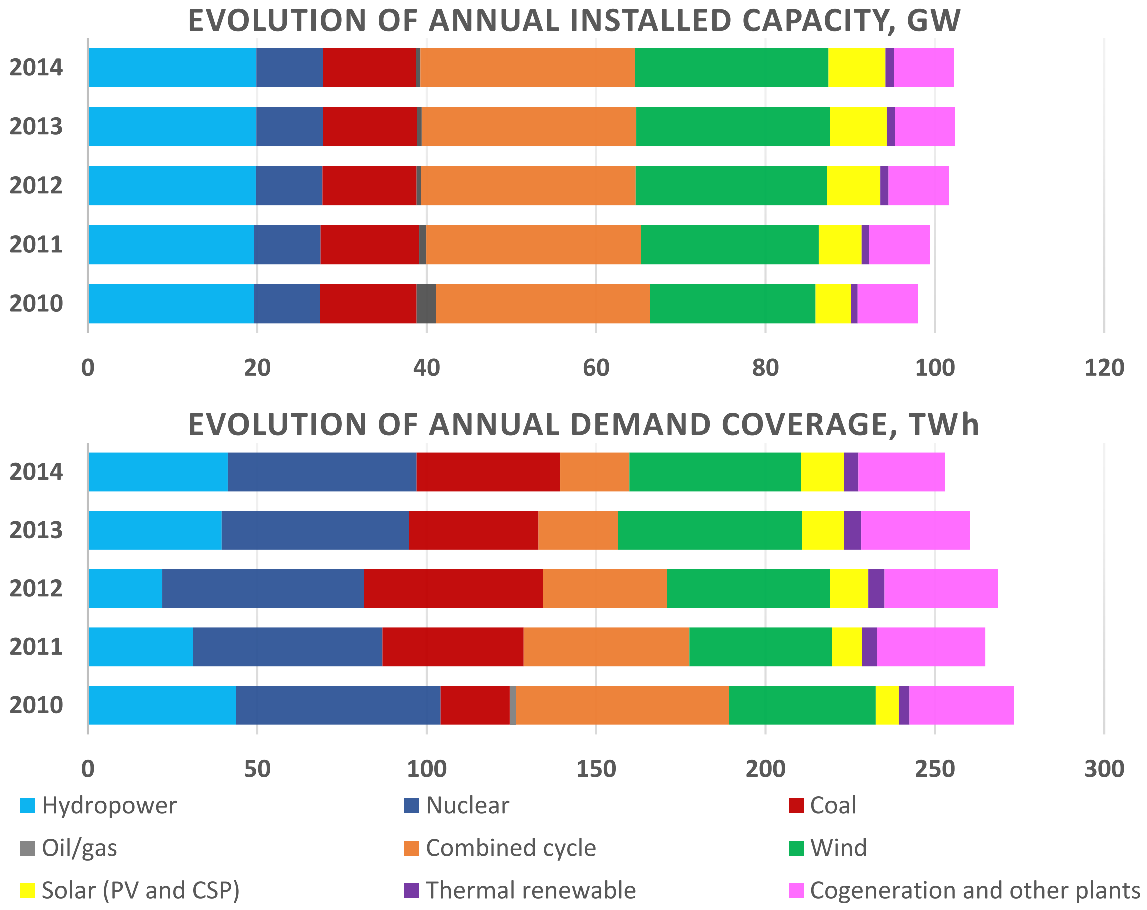

Figure 7.7 Evolution of annual installed capacity and annual demand coverage (Red Eléctrica de España, 2015a, p.8). Data collected from (Red Eléctrica de España, 2015a, p.32 and 33)

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7.1.3.3 Regional analysis of the electrical system

El sistema elcectrico español 2014 (Red Eléctrica de España, 2015b) supplies some interisting data about Spanish regions (*comunidades autónomas*). It provides the data about the electric generation (Table 7.8) and the installed capacity (Table 7.9) for all the regions by type of plant in 2014. Using these information, it is possible to draw two bar charts (Figure 7.8 and 7.9) which show the structure of the installed capacity region by region and the structure of the net production of electricity. These charts are very useful to have a rapid look at the structure of the system, and to simply notice where the system could be vulnerable to various climatic agents.

Table 7.8 2014 Spanish electrical energy balance for all regions (GWh) (Red Eléctrica de España, 2015a, p. 110 and 111)

	ANDALUCIA	ARAGÓN	ASTURIAS	BALEARES	C. VALENCIANA	CANARIAS	CANTABRIA	CASTILLA LA MAN	CASTILLA Y LEÓN	CATALUÑA
HYDROPOWER	1001	3408	1688	-	1760	0	681	531	10233	4392
NUCLEAR	-	-	-	-	9470	-	-	8320	0	23769
COAL	10070	5002	9244	2416	-	-	-	1035	8645	-
OIL/GAS	-	-	-	1298	-	4919	-	-	-	0
COMBINED CYCLES	4539	232	311	458	4136	3401	-	1087	-	5216
GEN CONSUMPTION	-713	-450	-721	-297	-500	-425	-10	-737	-751	-1228
HYDRO-WIND	-	-	-	-	-	1	-	-	-	-
OTHER HYDRO	287	998	281	-	38	3	205	541	742	1176
WIND	6450	4314	1141	6	2577	391	76	8388	12274	2867
SOLAR PV	1574	297	1	123	549	282	2	1681	839	413
CSP	2124	-	-	-	94	-	-	734	-	66
REN THERMAL	1420	349	644	2	41	9	86	183	249	150
COGEN AND OTHER	5244	2383	652	281	1801	0	832	764	1682	4806
NET GENERATION	31996	16534	13240	4287	19966	8580	1873	22528	33912	41626
PUMPING	-481	-441	-79	-	-1576	-	-851	-101	-1107	-361
IMPORT/EXPORT	6488	-6239	-2820	1298	7817	-	3272	-11247	-19883	5010
DEMAND (BUSBARS)	38003	9854	10341	5585	26206	8580	4294	11179	12923	46275

	CEUTA	EXTREMADURA	GALICIA	LA RIOJA	MADRID	MELILLA	MURCIA	NAVARRA	PAÍS VASCO	TOTAL
HYDROPOWER	-	3106	8382	96	114	-	77	127	264	35860
NUCLEAR	-	15817	-	-	-	-	-	-	-	57376
COAL	-	-	10069	-	-	-	-	-	-	46480
OIL/GAS	231	-	-	-	-	215	-	-	-	6663
COMBINED CYCLES	-	-	546	166	-	-	2419	390	3018	25919
GEN CONSUMPTION	-19	-649	-629	-5	-2	-14	-83	-22	-60	-7317
HYDRO-WIND	-	-	-	-	-	-	-	-	-	1
OTHER HYDRO	-	49	1863	64	93	-	51	537	141	7071
WIND	-	-	8314	948	-	-	511	2425	344	51026
SOLAR PV	-	1071	19	129	93	0	800	298	29	8199
CSP	-	1899	-	-	-	-	41	-	-	4959
REN THERMAL	-	215	575	7	270	-	54	306	169	4729
COGEN AND OTHER	-	14	2147	57	736	9	1494	710	2273	25887
NET GENERATION	212	21522	31287	1463	1304	210	5363	4772	3177	266853
PUMPING	-	-71	-262	-	-	-	-	-	-	-5330
IMPORT/EXPORT	-	-17160	-11575	187	27541	-	3205	-23	10722	-3406
DEMAND (BUSBARS)	212	4292	19451	1650	28845	210	8568	4748	16899	258117

Table 7.9 Installed capacity in Spain in 2014 divided by regions (MW) (Red Eléctrica de España, 2015b, p.113)

	ANDALUCIA	ARAGÓN	ASTURIAS	BALEARES	C. VALENCIANA	CANARIAS	CANTABRIA	CASTILLA LA MAN	CASTILLA Y LEÓN	CATALUÑA
HYDROPOWER	10510	1310	748	-	1279	1	389	781	4253	2104
NUCLEAR	-	-	-	-	1092	-	-	1077	466	3147
COAL	2071	1101	2474	510	-	-	-	541	2735	-
OIL/GAS	-	-	-	877	-	1729	-	-	-	520
COMBINED CYCLES	6035	1898	865	934	2902	918	-	771	-	4256
HYDRO-WIND	-	-	-	-	-	12	-	-	-	-
OTHER HYDRO	147	257	77	-	31	0.5	72	126	256	286
WIND	3324	1797	476	4	1193	154	35	3800	5652	1284
SOLAR PV	869	167	1	78	349	166	2	923	495	265
CSP	997	-	-	-	50	-	-	349	-	23
REN THERMAL	291	87	87	2	26	3	13	58	45	75
COGEN AND OTHER	932	599	156	86	654	33	312	466	642	1335
TOTAL	15719	7217	4885	1490	7577	3016	822	8884	14543	13293

	CEUTA	EXTREMADURA	GALICIA	LA RIOJA	MADRID	MELILLA	MURCIA	NAVARRA	PAÍS VASCO	TOTAL
HYDROPOWER	-	2292	3269	30	66	-	24	77	120	17792
NUCLEAR	-	2094	-	-	-	-	-	-	-	7866
COAL	-	-	2049	-	-	-	-	-	-	11482
OIL/GAS	99	-	-	-	-	85	-	-	-	3309
COMBINED CYCLES	-	-	1268	799	-	-	3318	1236	1998	27199
HYDRO-WIND	-	-	-	-	-	-	-	-	-	12
OTHER HYDRO	-	20	522	27	44	-	14	171	55	2106
WIND	-	-	3362	448	-	-	263	1016	194	23002
SOLAR PV	-	561	16	86	67	0.1	440	161	26	4672
CSP	-	849	-	-	-	-	31	-	-	2300
REN THERMAL	-	37	95	4	43	-	21	47	83	1018
COGEN AND OTHER	-	19	574	46	328	2	338	175	500	7196
TOTAL	99	5873	11154	1440	547	87	4450	2884	2975	107954

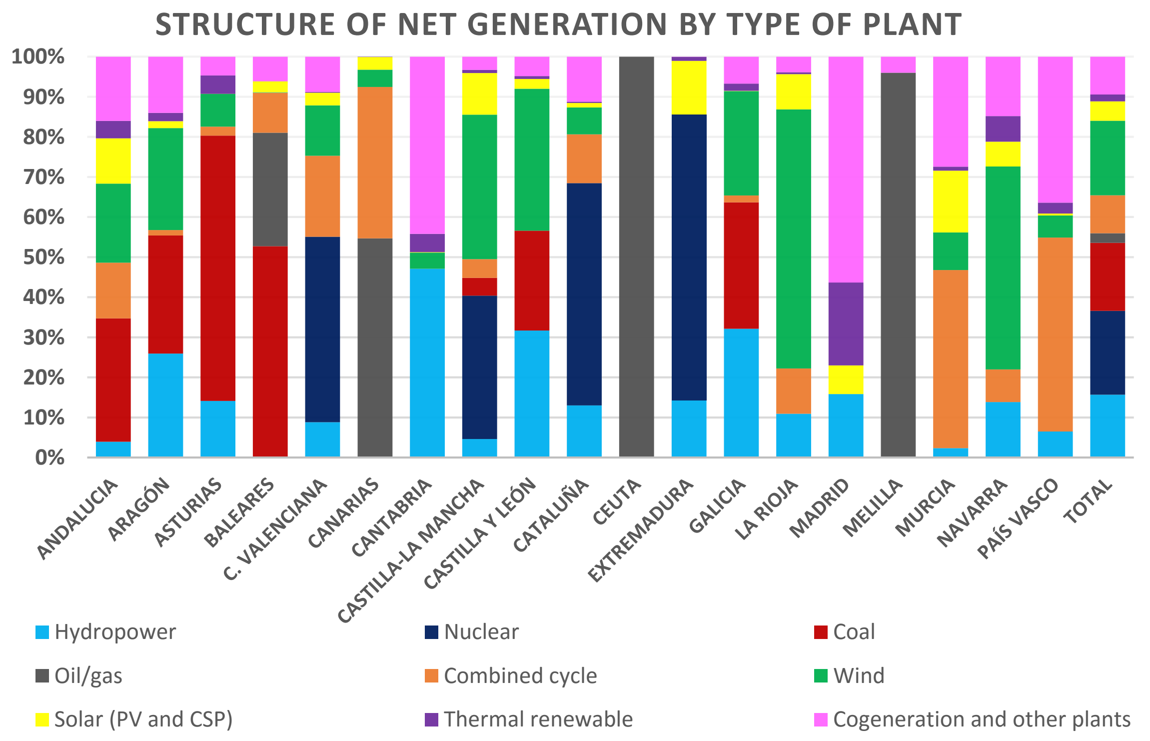

Figure 7.8 Structure of the 2014 Spanish net electricity generation by type of plant (Red Eléctrica de España, 2015b, p.3)

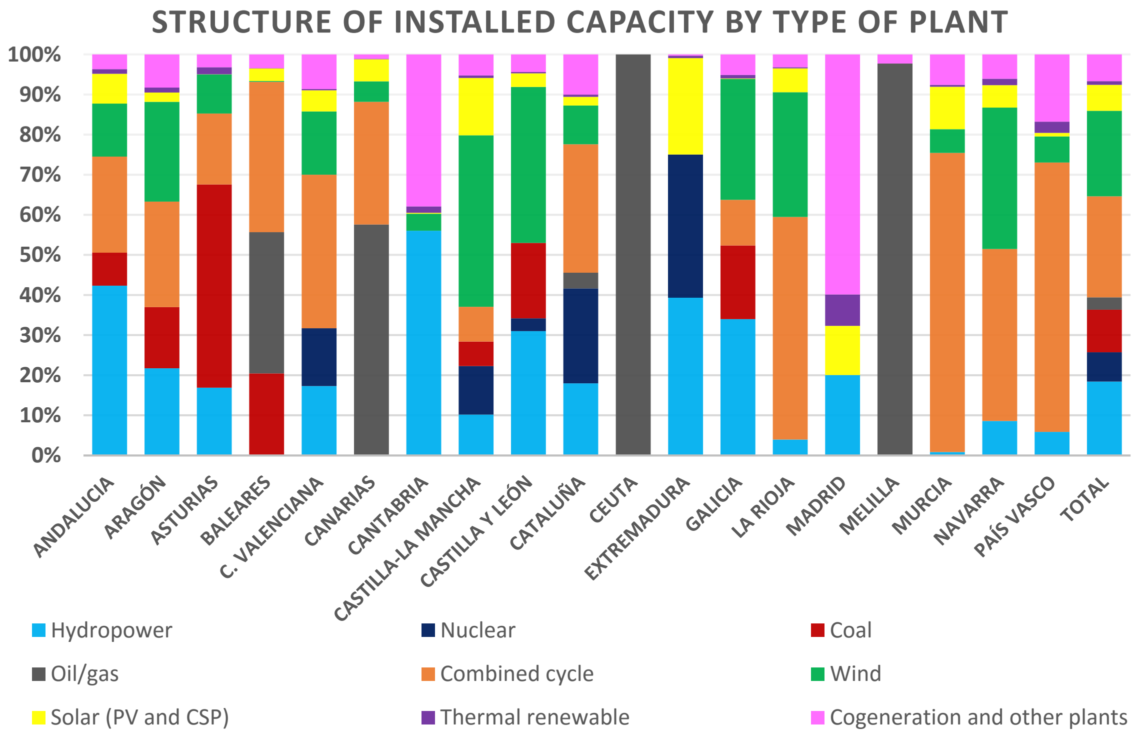

Figure 7.9 Structure of the 2014 Spanish installed capacity by type of plant (Red Eléctrica de España, 2015b, p.3)

Figure 7.11 (in the next page) then shows the location of the main thermal power plants of the entire Spain (peninsula, Canary Islands, Balearic Islands, Ceuta and Melilla) at December 2014. The map also shows the installed capacity of wind generators, photovoltaic panels and thermal panels for each region.

7.1.3.4 The transmission network

Table 7.10 displays the length of the Spanish transmission grid and the installed transformer capacity in the grid at 31 December 2014 (Red Eléctrica de España, 2015a). Figure 7.10 instead exposes the evolution of the peninsular transmission grid (400kV and <200kV) from 1975 to the present.

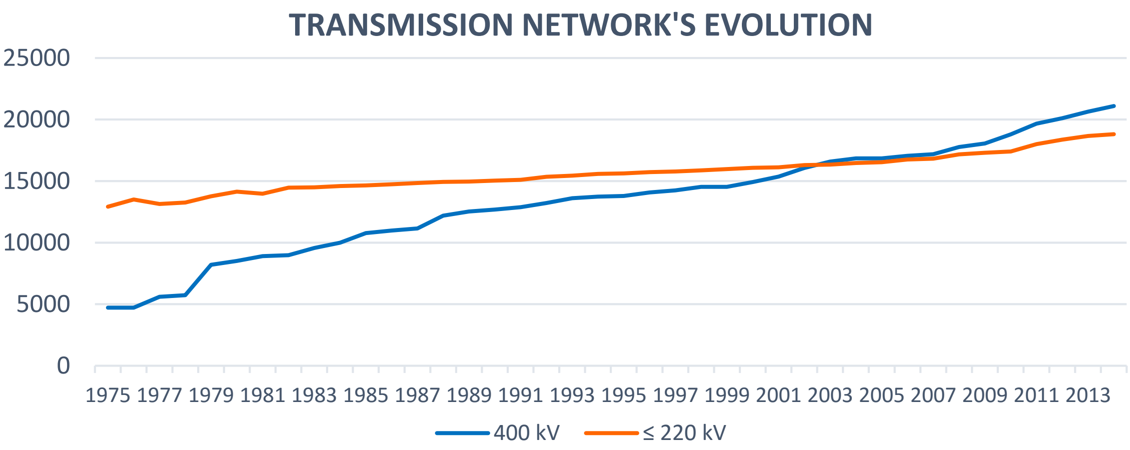

Figure 7.10 Evolution of the Peninsular Spanish transmission network (Red Eléctrica de España, 2015a, p.76)

Table 7.10 Spanish transmission network at 31 December 2014 (Red Eléctrica de España, 2015a, p.21)

	400 kV	**≤ 220 kV**			**TOTAL**
	PENINSULA	**PENINSULA**	**BALEARICS**	**CANARIES**	
Total cables (km)	21094	18811	1545	1289	42739
Overhead cables (km)	20977	18096	1089	1023	41185
Submarine cables (km)	29	236	306	30	601
Underground cables (km)	88	479	150	237	954

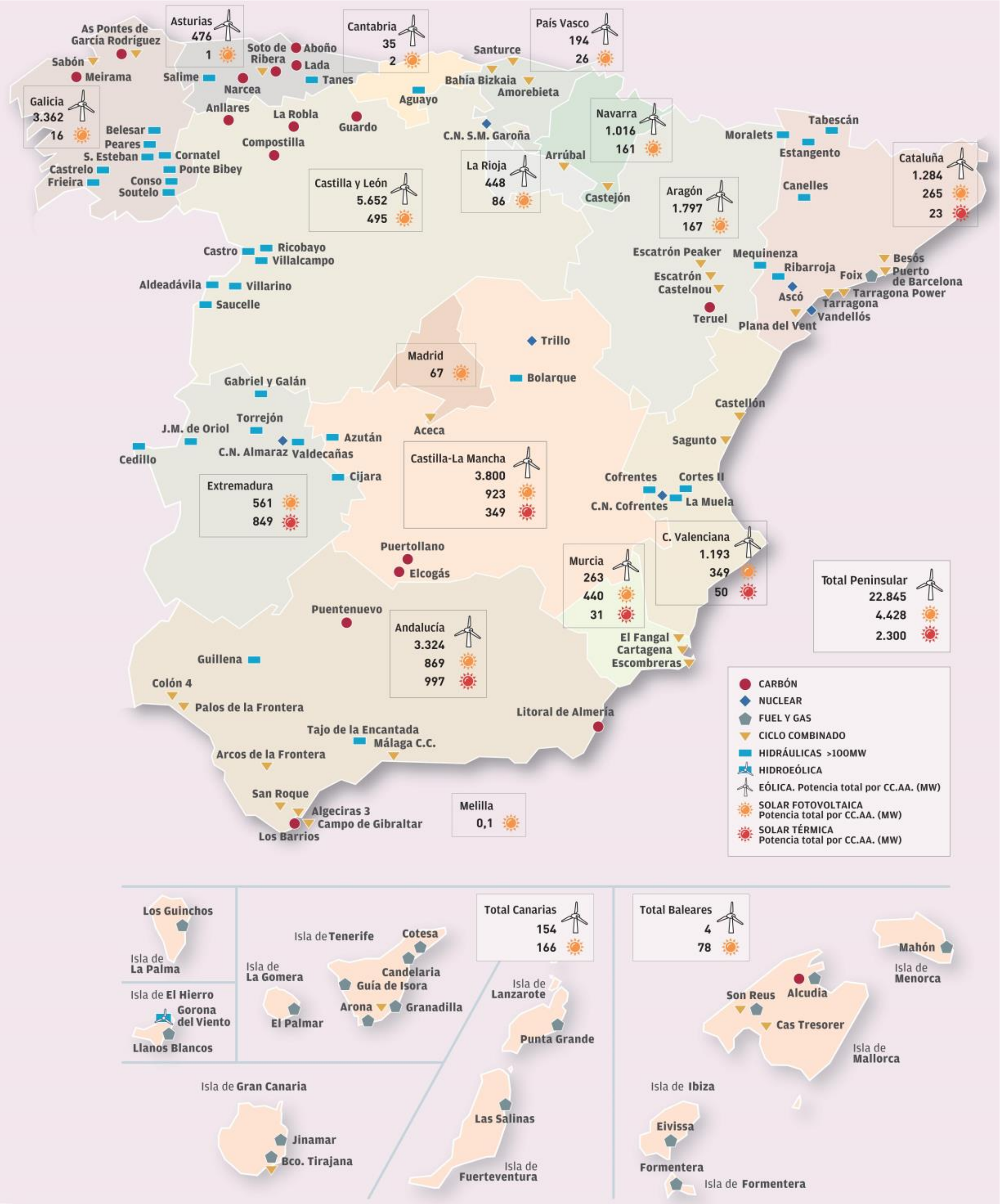

Figure 7.11 Main thermal power plants in Spain at December 2014 and renewable installed capacity per region (Red Eléctrica de España, 2015a, p.115)

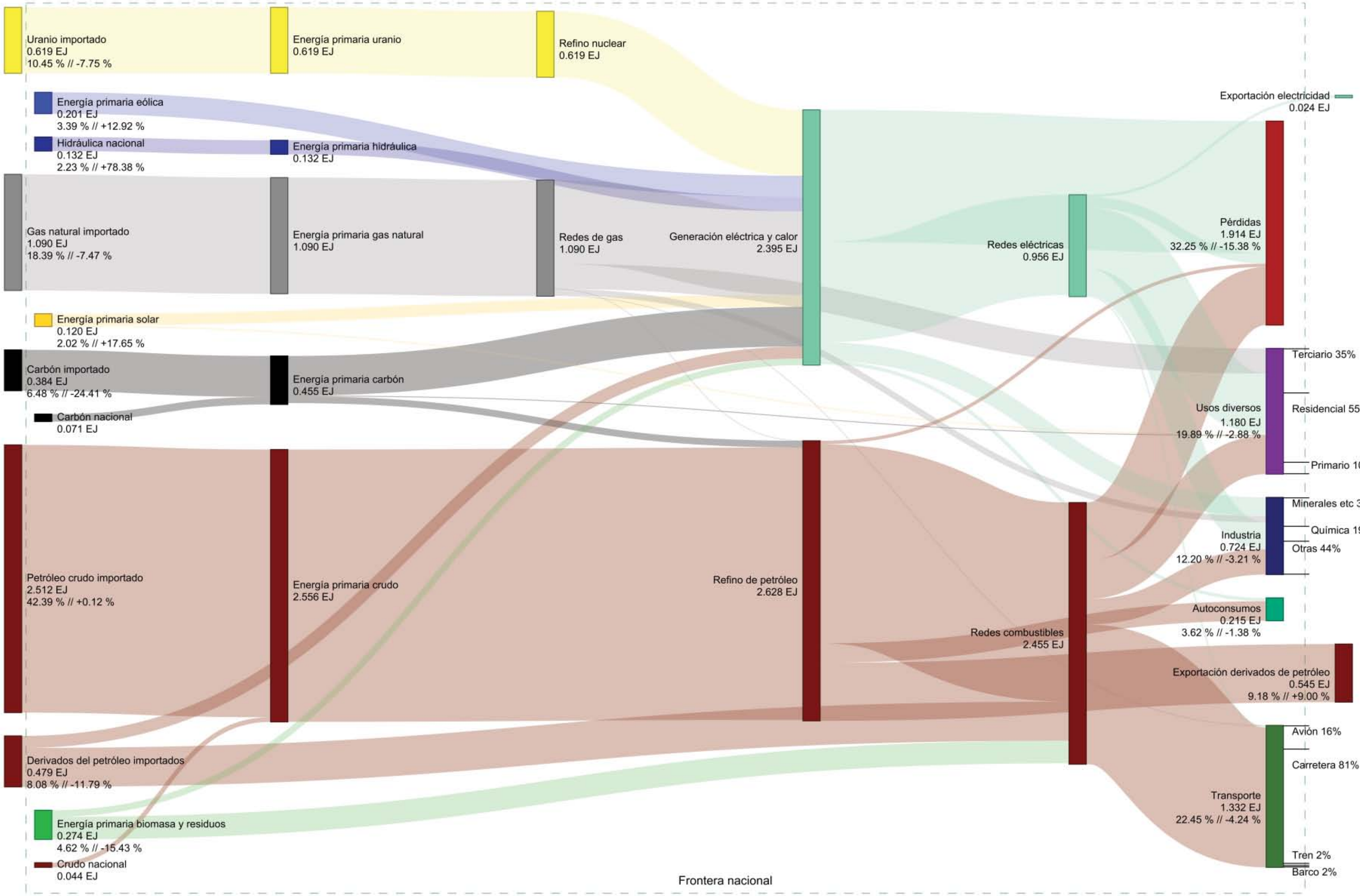

Figure 7.12 Sankey's diagram of the Spanish energy system (Catedra BP de Energía y Sostenibilidad, 2015, p.20)

7.1.3.5 Sankey's diagram

Finally, as a summary of the Spanish energy system, the Sankey diagram (Figure 7.12) realized by Catedra BP de Energía y Sostenibilidad in the *Observatorio de Energía y Sostenibilidad en España. Informe basado en indicadores. Edición 2014* (2015), manifests the evolution of each primary energy flow to its conversion into final energy. The thickness of each flow is proportional to its magnitude, measured in EJ.

7.2 The Italian energy system

7.2.1 The Italian overall energy balance

What is, what are its purposes and what is included and not included in an overall energy balance was already explained in Paragraph 7.1.1. Here we limit ourselves to report in Table 7.11 the 2013 overall energy balance realized by the Italian Department of Economic Development (Ministero dello Sviluppo Economico, 2014). The complete summary balance of the Italian Department of Economic Development includes the data about the year under review and the previous year, to make a comparison and calculate the percentage change of the various values.

Table 7.11 2013 Italian Energy Balance in billion tonnes of oil equivalent (Mtoe), based on 2013 Balances of Ministero dello Sviluppo Economico (2014)

2013	SOLID FUELS	NATURAL GAS	OIL	RENEWABLE[1]	ELECTRICITY	TOTAL
PRODUCTION	0.357	6.336	5.502	31.626	-	43.821
IMPORTS	13.485	50.756	77.815	2.304	9.754	154.114
EXPORTS	0.173	0.187	24.060	0.052	0.484	24.956
STOCK CHANGES	-0.494	-0.488	0.914	0.053	-	-0.015
TPES[2]	14.163	57.393	58.343	33.825	9.270	172.994
LOSSES IN ENERGY SECTOR	-0.142	-1.533	-3.822	-0.013	-40.897	-46.407
TRANSFORMATION IN ELECTR	-11.090	-16.876	-2.476	-25.901	56.343	0
TOTAL FINAL CONSUMPTION[3]	2.931	38.984	52.045	7.911	24.716	126.587
INDUSTRY	2.856	12.130	3.788	0.034	9.367	28.175
TRANSPORT	-	0.812	34.897	1.188	0.926	37.823
CIVIL	0.003	25.463	3.427	6.682	13.935	49.510
AGRICULTURE	-	0.129	2.112	0.007	0.488	2.736
NON-ENERGY USE	0.072	0.450	5.390	0.000	-	5.912
BUNKERS	-	-	2.431	-	-	2.431

Note. (1): net energy (pumping not considered). (2): Total Primary Energy Supply=production + imports – exports - stock changes. (3): Total final consumption=TPES + losses in energy sector + transformation in electricity

7.2.2 The Italian energy context

In the report *La situazione energetica nazionale nel 2014* (Ministero dello Sviluppo Economico, 2015) it is communicated the consumption of the entire Italian energy sector, which was

166.430 Mtoe (= 6.97 EJ: provisional data). In relation to the population, the website "Consumi di energia primaria" (n.d.), created by OPEF (*Osservatorio sulla Politica Energetica Fondazione Einaudi*), reported the fact that Italy has a quite low energy final consumption per capita. It was about 2.4 toe per capita in 2010, less than the average European value of 2.7 toe.

Tables 7.12 and 7.13 and Figure 7.14 describe the final energy and the primary energy consumption of Italy in 2013 and 2014 in Mtoe. These information were extracted from *Bilancio Energetico Nazionale 2013* (Ministero dello Sviluppo Economico, 2014) and from *La situazione energetica nazionale nel 2014* (Ministero dello Sviluppo Economico, 2015).

Table 7.12 Final energy consumption (Mtoe) (Ministero dello Sviluppo Economico, 2014). Provisional data from (Ministero dello Sviluppo Economico, 2015, p.21)

	2013	2014	RATE OF CHANGE %
SOLID FUELS	2.931	2.892	-3.37
NATURAL GAS	38.984	34.513	-11.46
OIL	52.045	51.506	-1.04
RENEWABLE ENERGIES	7.911	7.870	-0.5
ELECTRICITY	24.716	24.023	-2.8
TOTAL	126.587	12.804	-4.56

Table 7.13 Primary energy consumption (Mtoe) (Ministero dello Sviluppo Economico, 2014). Provisional data from (Ministero dello Sviluppo Economico, 2015, p.12)

	2013	2014	RATE OF CHANGE %
SOLID FUELS	14.163	13.466	-4.92
NATURAL GAS	57.393	50.704	-11.65
OIL	58.343	57.303	-1.78
RENEWABLE ENERGIES	33.825	35.342	+4.48
ELECTRICITY	9.270	9.615	+3.72
TOTAL	172.994	166.430	-3.79

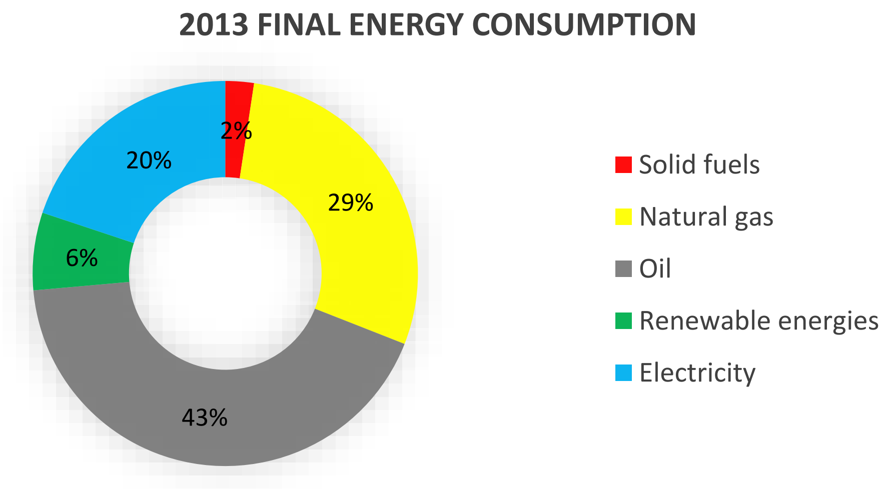

Figure 7.13 2014 Italian final energy consumption (Ministero dello Sviluppo Economico, 2015, p.21)

These data are useful to obtain the values of final and primary energy intensities. The economic recession, the re-composition of sectoral production and the higher energy efficiency decreased the 2014 energy needs of Italy by 3.8% (Ministero dello Sviluppo Economico, 2015). Whereas, the gross domestic product decreased only by 0.4%. These two values established a high reduction of energy intensity (-3.4% compared to 2013 energy intensity). The primary energy intensity's estimates of previous years were almost the same, as we can observe in Table 7.14, because energy demand and gross domestic product decreased in the same way. The analysis of the energy intensity trend is useful to note if there have been changes in the energy sector.

Table 7.14 Italy's primary energy intensity (Ministero dello Sviluppo Economico, 2015, p.13)

	2010	**2011**	**2012**	**2013**	**2014[1]**
GDP (M€)	1605694	1615117	1570372	1543702	1537125
ENERGY DEMAND (Mtoe)	187.79	184.20	176.31	172.99	166.43
ENERGY INTENSITY (toe/M€)	117.0	114.0	112.3	112.1	108.3

Note. (1): provisional data for 2014.

The bar chart of Figure 7.15 shows the evolution of the primary energy consumption by different sources in Italy. The necessary data for the development of this graph are gathered from the Italian overall energy balances from 2000 to 2013 and the document *La situazione energetica nazionale nel 2014* (Ministero dello Sviluppo Economico, 2015).

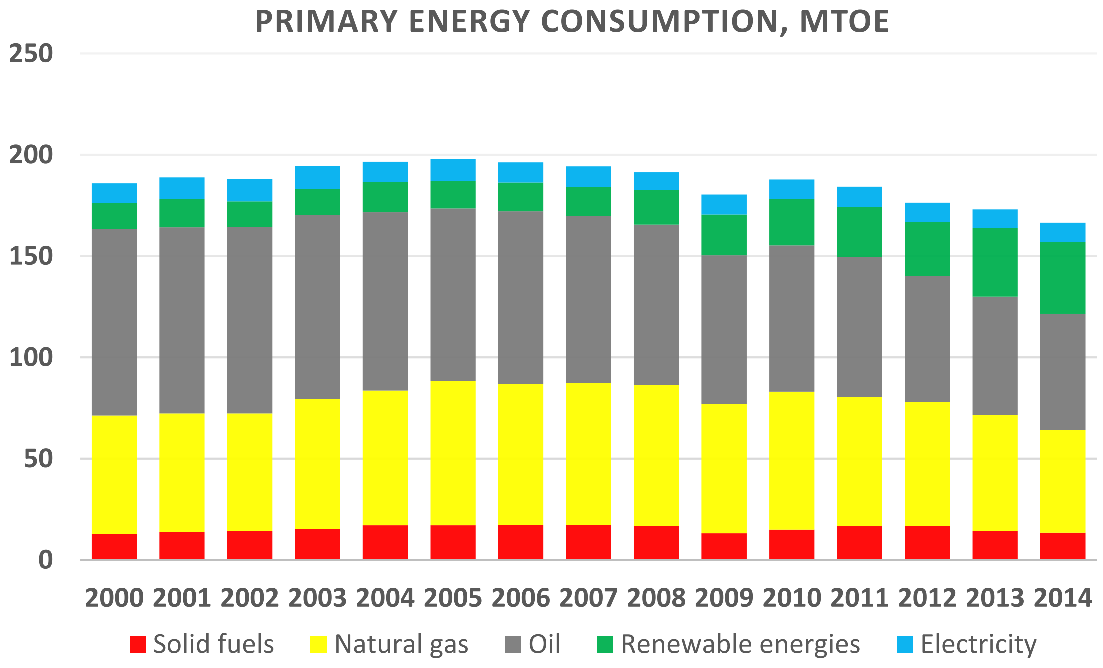

Figure 7.14 Primary energy consumption in Italy (Mtoe) from 2000 to 2014

The 2014 Italian demand of energy was characterized, compared to 2013, by a stability of oil (from 33.7% to 34.4%) and solid fuels (from 8.2% to 8.1%) and by a reduction of gas consumption (from 33.2% to 30.5%). The share of renewable resources continues to increase, passing from 19.5% to 21.2%. The pie charts of Figures 7.15 and 7.16 show the percentage of each renewable source in primary energy in 2012 and 2013 (data collected from *Rapporto statistico. Energia da fonti rinnovabili. Anno 2013* (Gestore dei Servizi Energetici, 2015, p.21).

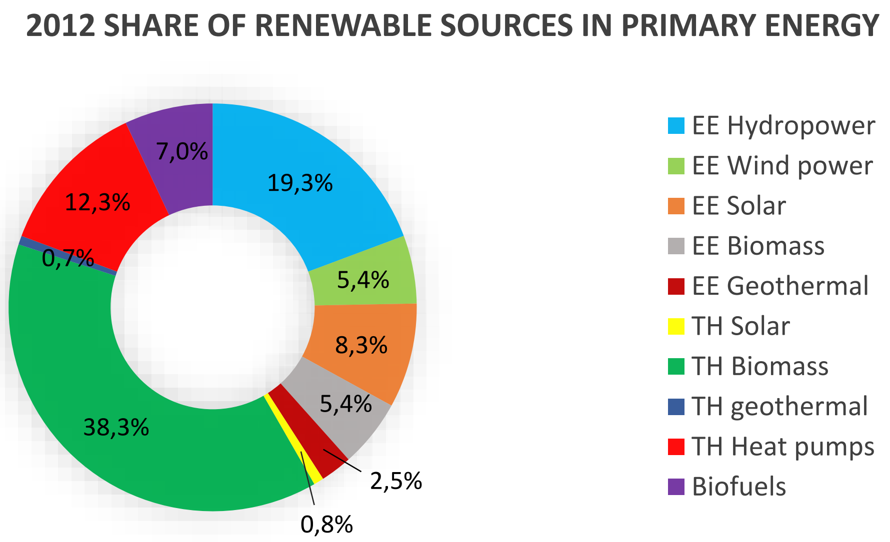

Figure 7.15 2012 Share of renewable resources in Italian primary energy (Gestore dei Servizi Energetici, 2015, p.19). EE means “electric energy”, whereas TH means “thermal energy”

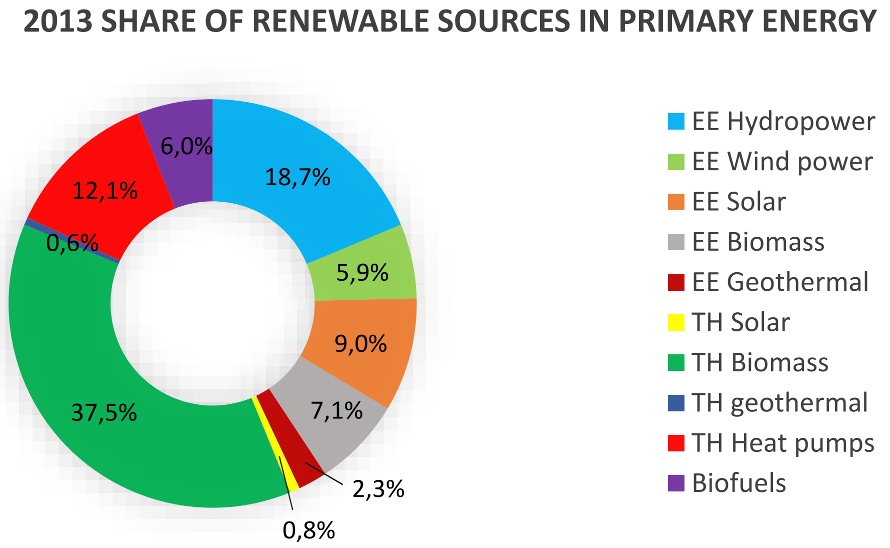

Figure 7.16 2013 Share of renewable resources in Italian primary energy (Gestore dei Servizi Energetici, 2015, p.19). EE means “electric energy”, whereas TH means “thermal energy”

7.2.3 The Italian electrical system

7.2.3.1 Electrical energy balance

In the report *Dati statistici sull'energia elettrica in Italia – 2014* (Terna, 2015a) we can find a comprehensive electricity energy balance for the years 2013 and 2014, with, for each element, the relative percentage change (Table 7.15).

Table 7.15 2013 and 2014 Italian electrical energy balances (Terna, 2015a, p.12)

GWh	2013	2014	2014/2013
GROSS GENERATION	**289803.2**	**279828.5**	**-3.4%**
HYDROPOWER	54671.6	60256.3	10.2%
THERMAL POWER	192986.8	176171.2	-8.7%
GEOTHERMAL	5659.2	5916.3	4.5%
WIND POWER	14897.0	15178.3	1.9%
PHOTOVOLTAIC	21588.6	22306.4	3.3%
CONSUMPTION OF AUXILIARIES	10970.5	10980.7	-2.6%
NET GENERATION	**278832.6**	**269147.9**	**-3.5%**
HYDROPOWER	54068.4	59574.9	10.2%
THERMAL POWER	183403.9	167080.2	-8.9%
GEOTHERMAL	5320.1	5566.6	4.6%
WIND POWER	14811.6	15088.6	1.9%
PHOTOVOLTAIC	21228.7	21837.5	2.9%
PUMPING	2495.2	2329.1	-6.7%
DISPATCHED ENERGY	**276337.4**	**266818.8**	**-3.4%**
IMPORTS	44337.9	46747.5	5.4%
EXPORTS	2200.2	3031.1	37.8%
DEMAND	**318475.1**	**310535.2**	**-2.5%**
GRID LOSSES	21187.5	19451.7	-8.2%
FINAL CONSUMPTION	**297287.6**	**291083.5**	**-2.1%**
AGRICULTURE	5677.1	5372.1	-5.4%
INDUSTRY	124870.8	122505.0	-1.9%
TERTIARY	99756.5	98951.4	-0.8%
DOMESTIC	66983.2	64255.0	-4.1%

In the document *Dati statistici sull'energia elettrica in Italia - 2014. Nota di sintesi* (Terna, 2015b) there is an account of the principle changes between 2013 and 2014.
First of all, the electricity demand decreased by 2.5% compared to 2013. The overall electricity demand in 2014 was 310.5 TWh. Final consumption fell by 2.1%: industry consumption diminished by 1.9%, domestic consumption by 4.1%, tertiary (commercial and public services) by 0.8% and agriculture by 5.4%. The share of renewable sources to electricity requirement increased in these years: photovoltaic production grew by 3.3%, hydropower generation by 10.9% and biomass by 9.6%. However, the record in power generation still remains to natural gas with a share of 54.5% in electric generation.

Table 50 of *Dati statistici sull'energia elettrica in Italia – 2014* (Terna, 2015a, p.155) provides the country electricity demand for each year from 1883 to 2014. It also provides the balance between electricity imports and exports. With these data it is possible to design the graph in Figure 7.17 about the Italian evolution of electricity demand.

7.2.3.2 The coverage of the demand

The installed capacity for electricity production in Italy at 31 December 2014 amounted to 121.762 GW, with a reduction of 2.753 GW (-2.2%) than 2013 capacity. This decrease was the

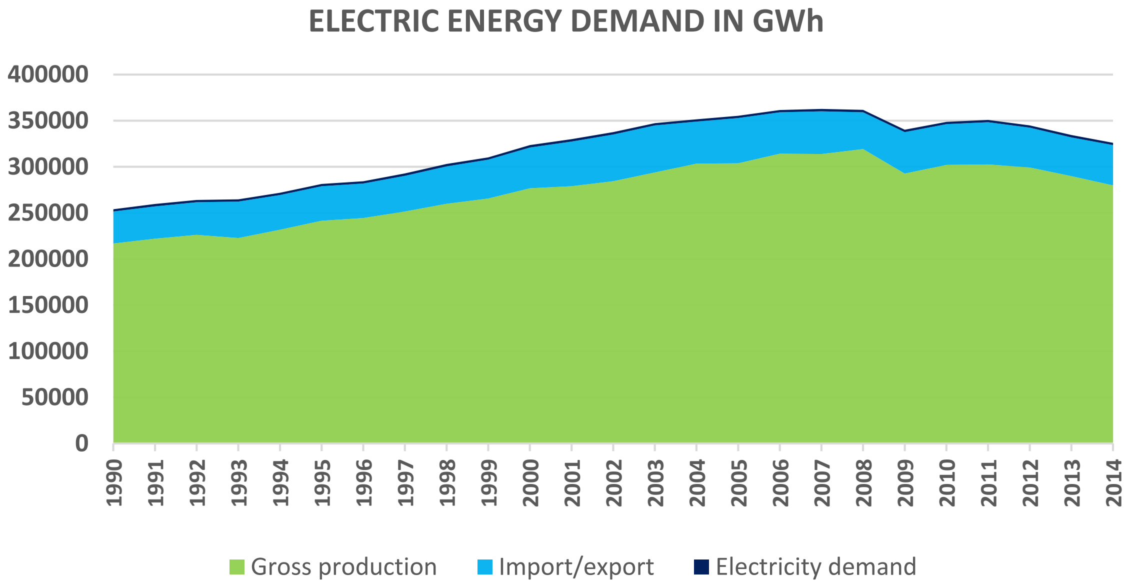

Figure 7.17 Evolution of electric Italian energy demand in GWh (Terna, 2015a, p.157)

result of the disposal of some thermoelectric power plants. Vice versa, the photovoltaic sector increased by 2.3% than 2013, with 424 MW more.

The reduction of thermoelectric capacity has not to suggest that other types of electricity plants are taking over the thermal generation. Thermoelectric generation settled at 62.1%. Among the fuels used for thermal generation, the primacy still remained to natural gas with 91.1 TWh (the 54.4% of overall thermoelectric production). Gas is followed by coal, with a share of 22.8% (39.4 TWh, with a decrease of 3.4% compared to 2013).

These data were collected from the document *Dati statistici sull'energia elettrica in Italia – 2014* (Terna, 2015a) and *Dati statistici sull'energia elettrica in Italia - 2014. Nota di sintesi* (Terna, 2015b). These statistics, with other deduced from previous Terna's reports, were used to elaborate the diagrams in Figure 7.18 and 7.19, which portray the state of the electrical capacity and production in Italy in 2014, and their evolution in recent years.

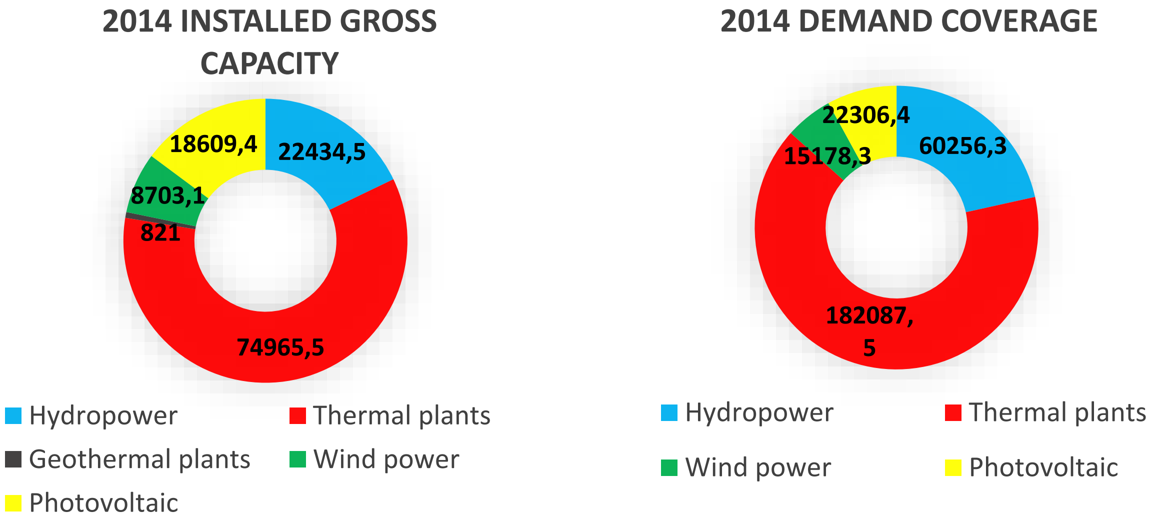

Figure 7.18 Installed capacity at 31.12.2014 in the Spanish electrical system: data in MW from (Terna, 2015a, p.31). 2014 demand coverage in the Italian electrical system: data in GWh (Terna, 2015a, p.86)

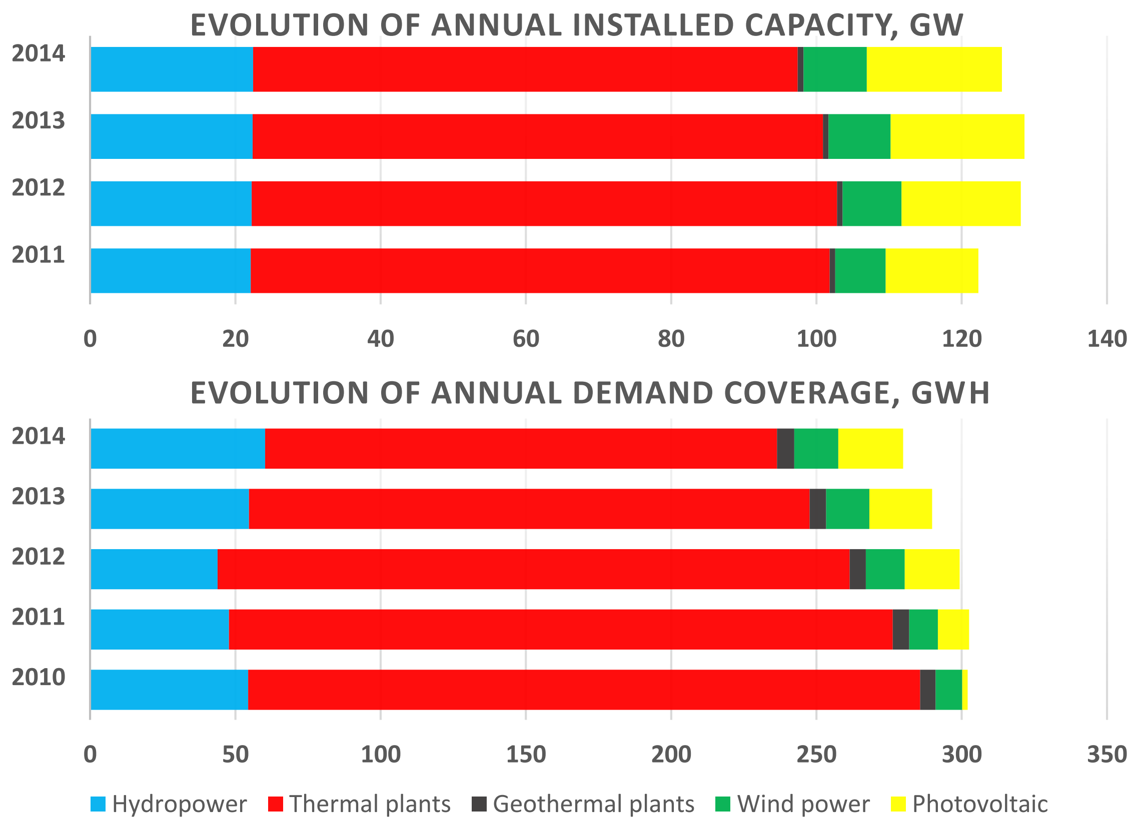

Figure 7.19 Evaluation of annual installed capacity and annual demand coverage

7.2.3.3 Regional analysis of the electrical system

The Terna's report *Dati statistici sull'energia elettrica in Italia – 2014* (2015a) supplies not only information at national level but also at regional one. Table 27 at page 92, table 30 at page 98 and table 35 at page 113 of the Terna's report were used to elaborate Table 7.16, which resumes the data about the electricity production for all Italian regions by type of plant for 2014. Figure 7.20 describes in graphic form the statistics in Table 7.16.

Table 7.16 Italian electricity generation for all regions (GWh) (Terna, 2015a)

GWh	HYDROPOWER	THERMAL PLANTS	WIND POWER	PHOTOVOLTAIC PANELSS	BIOMASS
PIEMONTE	8778.0	12784.0	26.1	1646.5	1731.3
VALLE D'AOSTA	3431.0	11.9	3.7	22.7	11.9
LOMBARDIA	13977.0	26295.2	0.0	2046.1	4249.3
TRENTINO A.A.	13287.9	1400.7	1.2	407.1	340.4
VENETO	5559.1	11205.2	17.9	1784.1	1898.7
FRIULI V.G.	2540.6	6123.3	0.0	509.3	706.1
LIGURIA	350.4	6888.6	117.3	96.1	125.5
EMILIA ROMAGNA	1301.7	13797.9	27.2	2093.1	2759.0
TOSCANA	1060.7	13180.4	220.6	847.8	604.0
UMBRIA	1824.4	814.1	3.0	526.6	223.5
MARCHE	608.4	495.2	1.8	124.9	186.5
LAZIO	1316.9	17280.1	87.1	1572.2	704.3

ABRUZZO	2142.3	1282.3	335.8	861.4	161.1
MOLISE	240.7	1264.4	681.1	217.9	164.8
CAMPANIA	1066.6	4835.3	2046.8	855.8	1026.4
PUGLIA	4.4	30188.3	4297.5	3612.2	1650.4
BASILICATA	314.5	531.3	825.6	481.3	214.0
CALABRIA	1521.0	5592.8	1906.3	636.3	1024.3
SICILIA	471.1	17249.2	2922.4	1893.3	259.2
SARDEGNA	459.7	10867.2	1657.0	952.5	689.6
TOTAL	60256.3	182087.5	15178.3	22306.4	18732.4

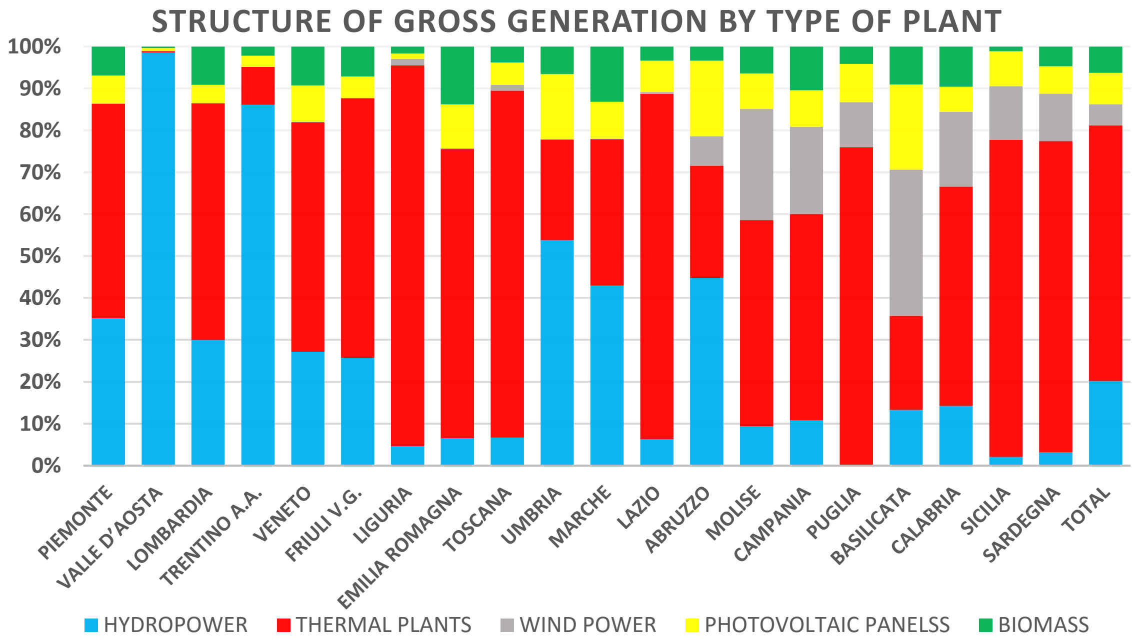

Figure 7.20 Structure of the 2014 Italian gross electricity generation by type of plant

Finally, Figure 7.21 shows the place of the principal hydro, gas, oil, wind, solar and biomass power plants on the territory.

7.2.3.4 Imports and exports

The amount of electricity exchanged with foreign countries is reported in detailed in the document *Dati statistici sull'energia elettrica in Italia – 2014* (Terna, 2015a, p.20). In Table 7.17 we display the imports and exports with other countries for the years 2013 and 2014.

Table 7.17 Imports to and exports from the Italian electric system. Data collected from (Terna, 2015a, p.20)

GWh	FRANCE	SWITZER LAND	AUSTRIA	SLOVENIA	GREECE	TOTAL
2013 IMPORTS	12536.0	23341.5	1506.2	5316.5	1637.7	44337.9
2013 EXPORTS	857.5	1094.7	20.1	132.5	95.4	2200.2
2014 IMPORTS	15520.2	24414.2	1535.2	5170.0	107.9	46747.5
2014 EXPORTS	732.7	819.7	27.5	117.1	1334.1	3031.1

In 2014 national electricity generation met the 85.9% of the electricity demand, for a total amount of 266.8 TWh, with a reduction of 3.4% related to 2013. The remaining share of electricity demand (14.1%) was covered by net electricity imports, for an amount of 43.7 TWh, 3.7% more than the previous year.

Figure 7.22 illustrates the exchanges of electricity energy with neighboring countries from 1963 to 2014 (Terna, 2015a, p.21).

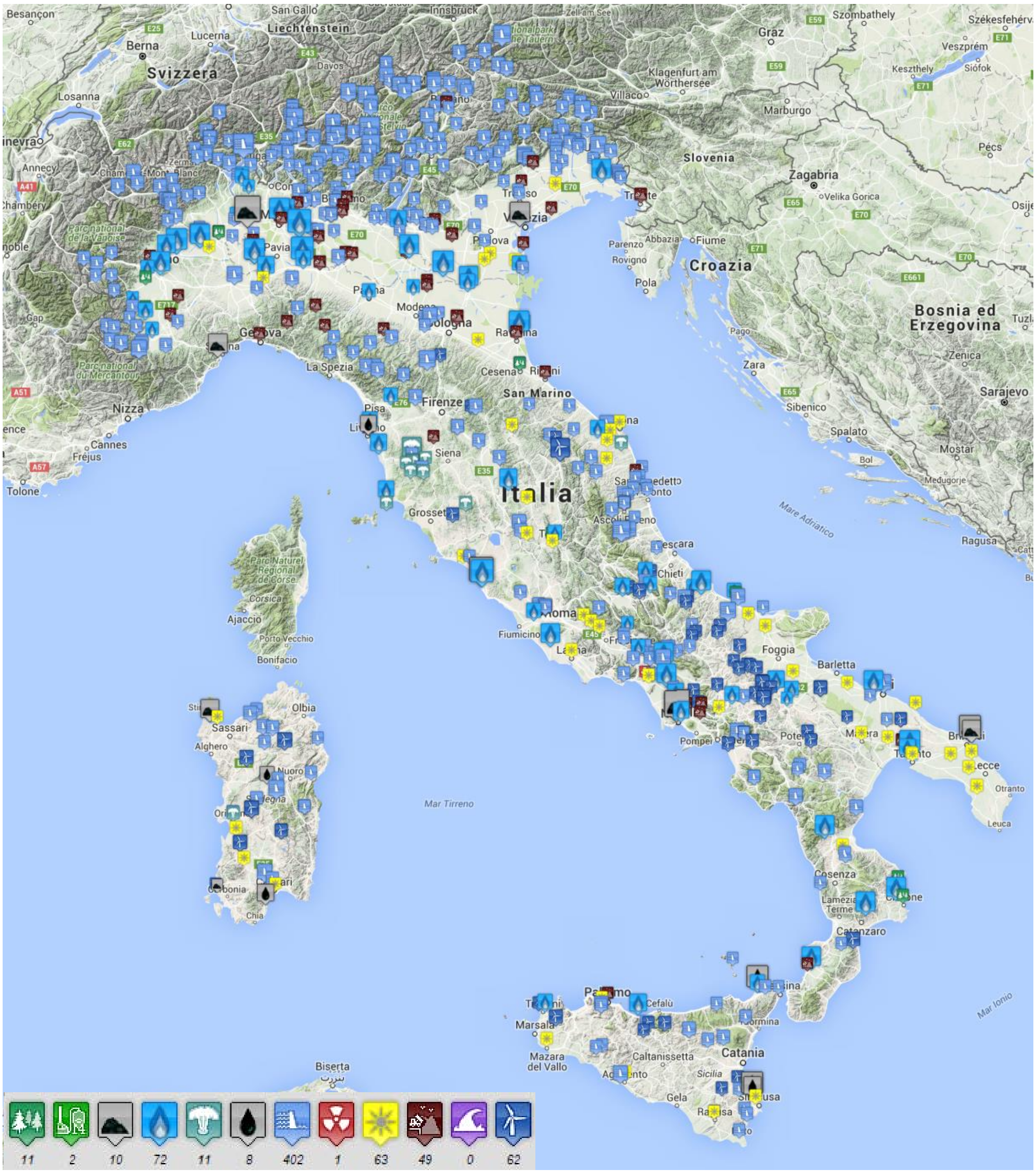

Figure 7.21 Main power plants in Italy ("Enipedia Maps Sandbox," n.d.). The symbols in the legend in order means: biomass, biogas, coal natural gas, geothermal, oil, hydro, nuclear, solar, waste, wave, wind.

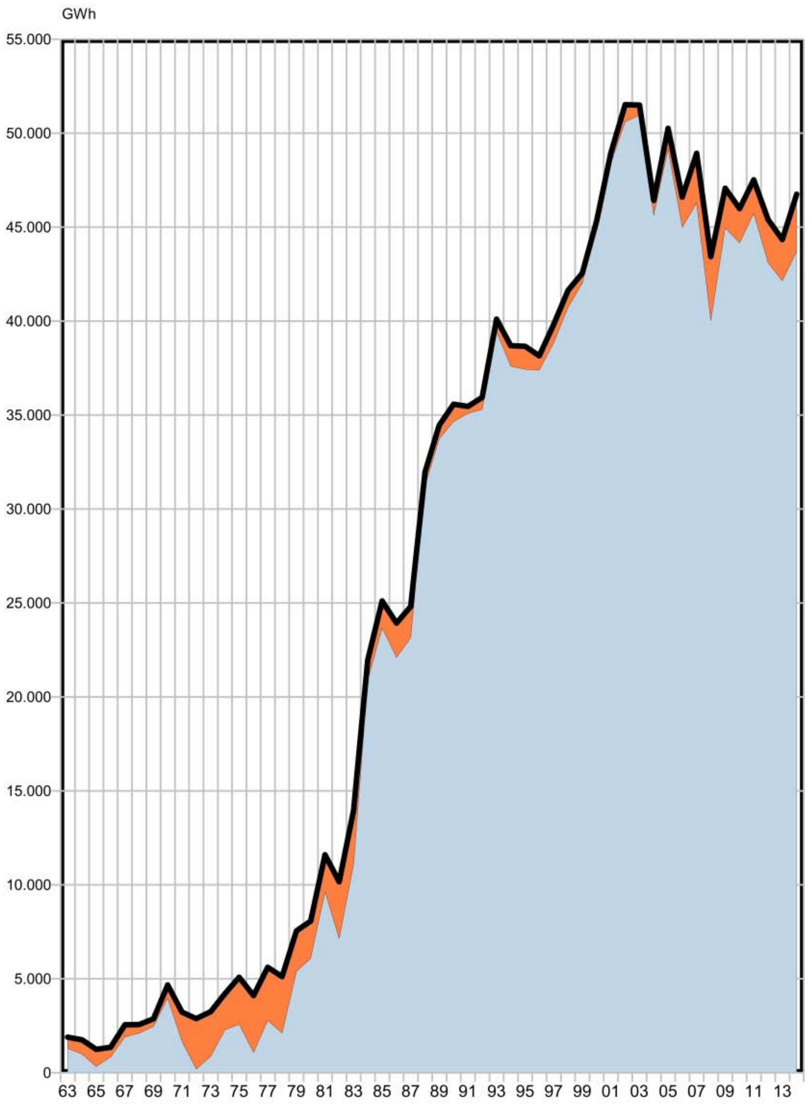

Figure 7.22 Physical exchanges of electricity energy with neighboring countries from 1963 to 2014 (Terna, 2015a, p.21)

7.2.3.5 The transmission network

The Italian national transmission network (RTN: Rete di Trasmissione Nazionale) is composed principally by cables at 380 kV and 220 kV. Actually, RTN is constituted by cables with operating voltage greater or equal to 120 kV. Three direct current lines (HVDC) also belong to the national transmission grid. These are the HVDC 500 kV SA.PE.I between Lazio and Sardinia, the HVDC 400 kV line between Italy and Greece and the HVDC 200 kV SA.CO.I between Tuscany, Corsica and Sardinia. In Table 7.18 we resume the length of the network, while Figures 7.23 and 7.24 illustrate the Italian 380 kV grid at 31 December 2014 and the Italian 220 kV grid at 31 December 2014.

Table 7.18 Italian transmission network at 31 December 2014 (Terna, 2015a, p.25)

	380 kV	220 kV	TOTAL
Total cables (km)	10995.9	10935.2	21931.1
500 kV DC SA.PE.I. (km)		949.2	
400 kV DC Italy-Greece (km)		254.9	
200 kV DC SA.CO.I. (km)		861.6	

7.2.3.6 Sankey's diagram

Finally, we can summarize the Italian energy system showing a Sankey diagram (Figure 7.25) realized by the IEA (IEA Sankey Diagram - Italy Balance 2012, IEA, n.d.).

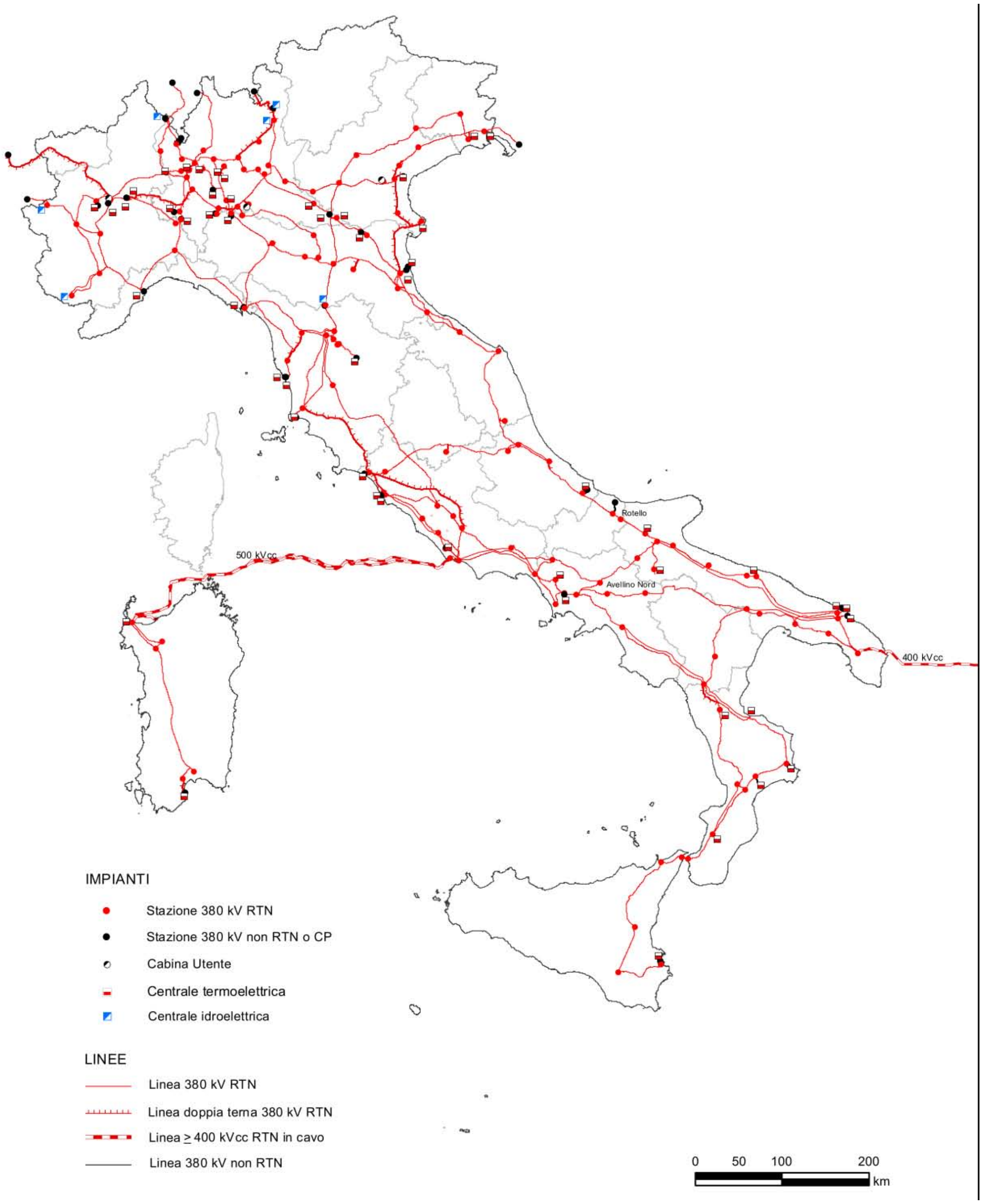

Figure 7.23 The 380 kV Italian transmission grid at 31 December 2014 (Terna, 2015a, p.26)

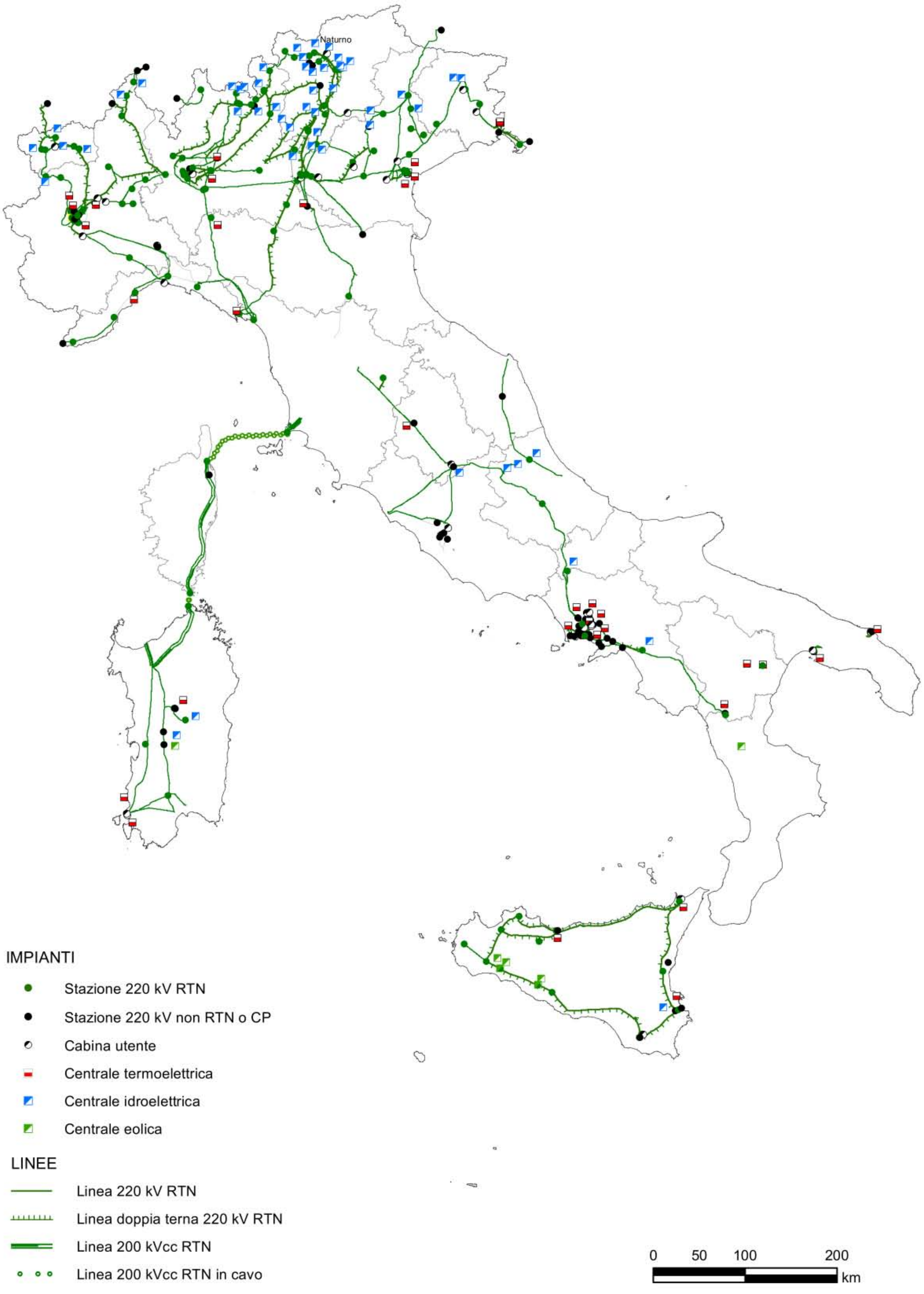

Figure 7.24 The 220 kV Italian transmission grid at 31 December 2014 (Terna, 2015a, p.27)

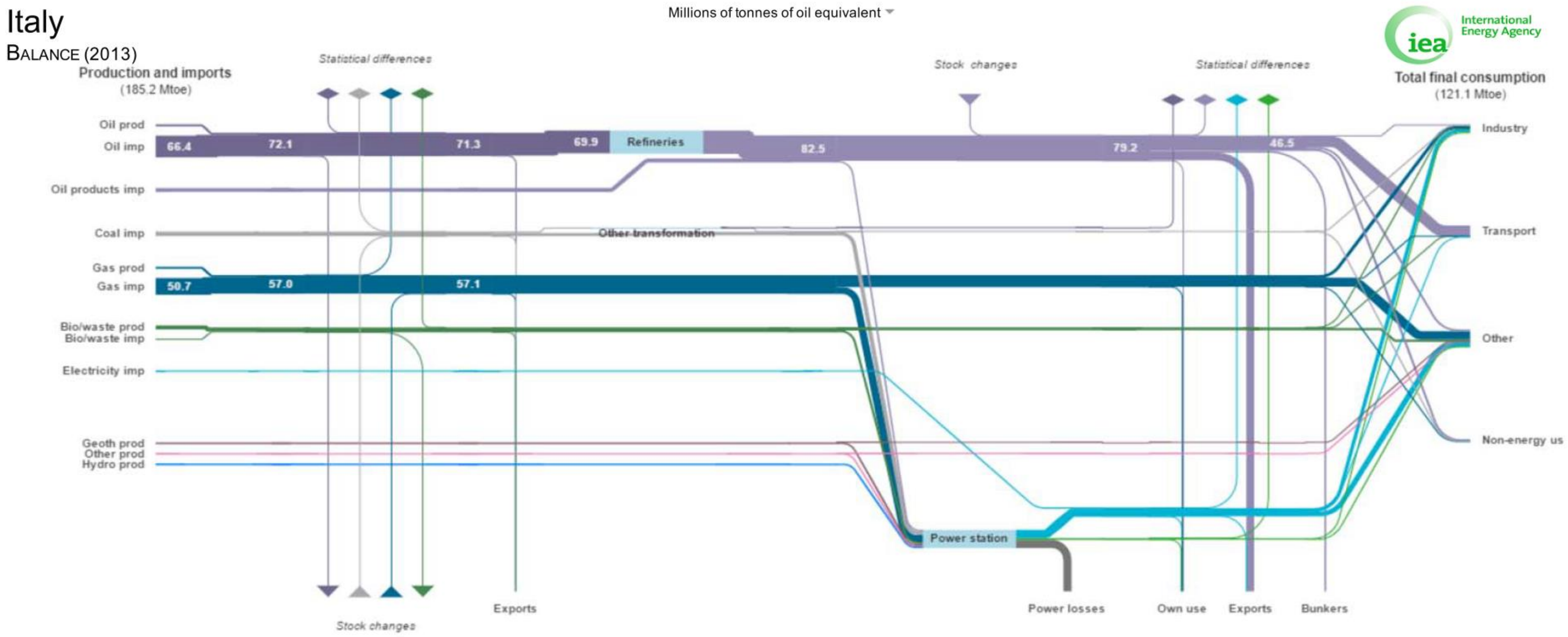

Figure 7.25 Sankey's diagram of the Italian energy system (IEA, n.d.)

CHAPTER 8

CLIMATE CHANGE AND CLIMATE CHANGE'S IMPACTS ON SPAIN AND ITALY

This chapter of the case study focuses on climate change and climate change impacts on the Spanish and Italian energy system. This research is carried out using as guideline the structure of climate change impacts on energy systems developed in Chapter 2, represented by the figure of the paths of climate impacts (Figure 8.1).

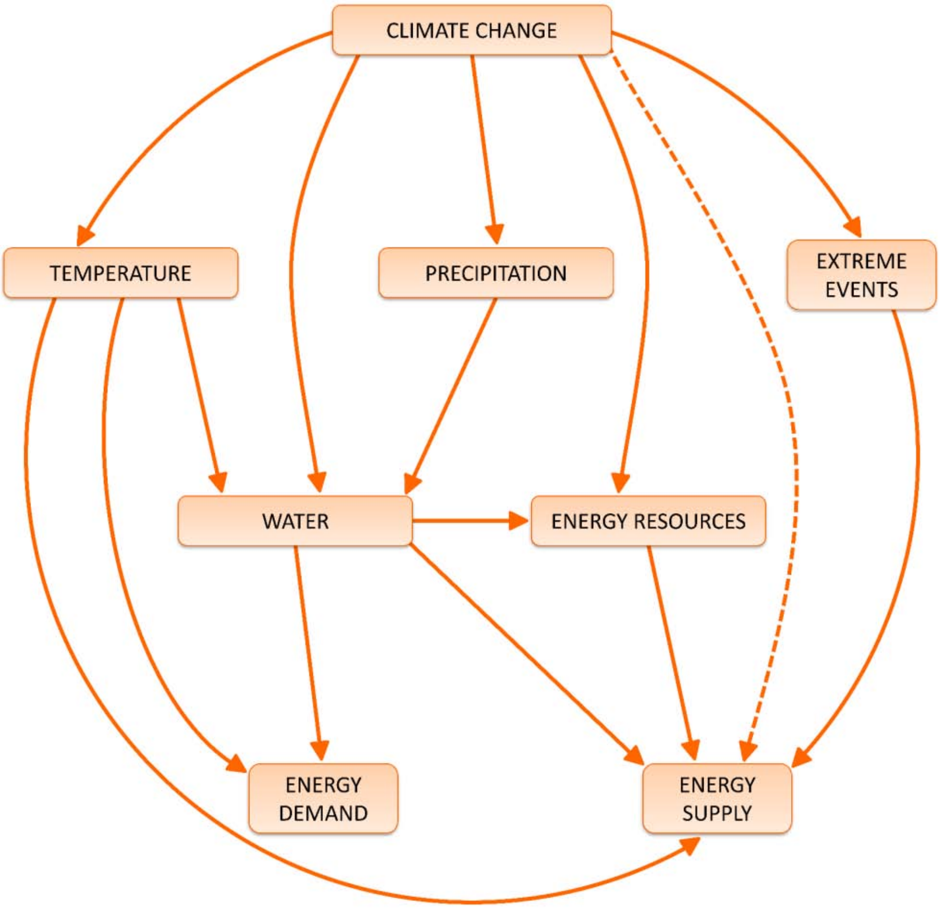

Figure 8.1 Structure of climate change's impacts on energy systems. Created by author

Differently from the general method, in this section we will not rest extensively on the magnitude of the various changes and impacts, but we will only assess their major trends.

As primary reference for this analysis, we use the information of the website of the Centre for Climate Adaptation ("Home - Climate Adaptation," n.d.). The aim of this website is to summarize the impacts of climate change in Europe countries, collecting information from a large number of publications, including the IPCC Assessment Reports, the EU Reports of the European Environmental Agency and Joint Research Centre, National studies and scientific journals. Throughout the assessment we will refer also to other references which will be punctually reported. For further and more detailed information and data we refer to the summary tables in Chapter 9.

The assessment will be divided in two parts, as in the global approach: the first one concerns natural and physical system, while the second one regards the impacts of climate change on the energy systems.

8.1 Climate change in Spain and Italy

The evaluation of physical impacts of climate change on the Spanish and Italian natural systems is the starting point of the assessment. Following the general pattern, we will give an account of the principal climatic consequences of climate change, which are the changes of temperatures, precipitation patterns and extreme events.

8.1.1 Temperature changes

As the general trend, the Global Mean Surface Temperature (GMST) is expected to rise in the next decades. The magnitude of the projections will depend on the model used to obtain the data, the considered scenario, the season in concern, the region and the time horizon.
The study *EURO-CORDEX: new high-resolution climate change projections for European impact research* (Jacob et al., 2014) carried out climate change projections for various areas of the European continent. Three different areas could be found in the two countries we consider: the southern, the alpine and the Atlantic (the southern in Spain and Italy, the alpine only in Italy and the Atlantic only in Spain). They estimated a rise of the GMST at the end of the 21st century between 2 and 4°C in general, with higher values in the alpine region and lower in the Atlantic.
In the Climate Adaptation website, it is reported that in Spain the temperature in the coast would rise by some 2°C less than the hinterland, reaching also +7°C than the temperature at the end of 20th century. Italy and also Spain will manifest different temperature rises throughout the seasons, with peaks during summers, and throughout the country, because the rise of temperature in coastal regions will keep on +2°C thanks to the sea.
Also the study *21st century climate change in the European Alps—A review* (Gobiet et al., 2014) strengthens the estimation of different GMST rises trough the seasons, with higher projections during summers.

The ocean and sea temperatures will be modified in the future. The Mediterranean Sea is warming in both shallow and deep waters: this warming is part of global climate trends and it is not a regional phenomenon. According to *The future of the Mediterranean: From impacts of climate change to adaptation issues* (IDDRI, 2009) the Mediterranean sea surface temperature will rise of about 2°C at the end of the 21st century. The Adriatic Sea will suffer a higher increase, reaching +2.5°C.

Even the water of inland basins will rise its temperature. It is estimated that mean summer water temperature will increase up to 2.3°C at the end of the century comparing with the period 1971-2000.

8.1.2 Precipitation changes

Precipitation patterns will change in the future due to climate change. Nevertheless, projections do no always agree because they depend on several parameters, like temperature, water vapor (moisture) and energy, but also GHG concentrations and interactions between aerosols and clouds, which make difficult a unanimous interpretation. Having a look through the world, models indicate that precipitation generally increases at high latitudes, in both winter and summer seasons, and in areas of regional tropical precipitation maxima, with general decreases in the subtropics. Spain and Italy are among the northern latitudes and the tropics: this position creates some problems and disagreements over the projections.

For Jacob et al. (2014), that divided Europe in five sub-regions for realizing their simulations, Spain will see an increase of precipitation in the Atlantic region, as Italy in the Alps, whereas the rest of the two countries will suffer a decrease of precipitation in a range between -0% to -27%.

Gobiet et al. (2014) focused on Italy and especially on the Alpine region, predicting a low decrease in summer and a high increase in winter precipitation in the near term, while a high decrease in summer and a low increase in winter in the long term.

In the Climate Adaptation website there is a more specific dissertation. Spain will suffer a decrease in precipitation all over the territory, which will accelerate at the end of the century. The south (Andalusia) will experience a high reduction of precipitation as the Pyrenees region. Italy will be subjected to an increase of precipitation in winter and a decrease in summer, and an increase in the north and a decrease in the south.

8.1.3 Extreme events changes

To make the analysis of extreme events easier, we could divide the extreme events into four categories: extreme events of temperature, precipitation, atmospheric circulation and sea level.

Temperature's extreme events normally are evaluated considering future changes in warm and cold days. According to the study *EURO-CORDEX* (Jacob et al., 2014) in Spain there could be an increase of more than 100 warm days at the end of the century, as in Italy. The Atlantic and Alpine regions will be less affected than the rest of the countries. However, they imagined that one summer in two could be hot as the 2003 summer in 2100, and six winter in 10 as hot as record 2006-2007.

Other reports recapped in the Climate Adaptation website ("Home - Climate Adaptation," n.d.) studied specific region of the two countries. The Basque country in Spain will experience a -50% of frost days by 2100. Cold wave episodes (6 consecutive cold days) are expected to disappear beyond 2020. The north of Italy then will experience an increase of 3-5 weeks of heat wave days by 2060, whereas the coasts only two weeks.

Differently from temperature, there are non-consensus on extreme precipitation changes. In accordance with *Climate: Observations, projections and impacts – Spain* (Met Office, 2011a), for example, there remains uncertainty over extreme short-term precipitation in Spain. Nevertheless, Jacob et al. (2014) projected an high increase of extreme precipitation in the Atlantic and Alpine region, whereas the intensification in the rest of the countries will stop at about +50%.

Extreme atmospheric phenomena, like storms, are expected to relative change by the end of the 21st century relative to recent climate conditions. Mainland Spain, as Italy, will be not impacted by tropical cyclones as reported in *ENSEMBLES: Climate Change and its Impacts: Summary of research and results from the ENSEMBLES project* (van der Linden and Mitchell, 2009).

Extreme sea level rise impacts could be large in the absence of adaptation. It is considered that sea level rise has led to a change in extreme coastal water levels. On the basis of studies and observed trends, it is very likely that mean sea level will continue to rise in future. By the way, recent regional studies provide evidence for projected future declines in extreme wave height in the Mediterranean Sea.

8.2 Climate change's impacts on Spanish and Italian energy systems

As previously stated during the analysis of a generic system, we consider the energy sector divided into three main aspects: energy resource, energy demand and energy supply. Water is considered as an energy resource but it is examined apart from this group because it has a great importance in the whole energy sector.

The characterization of climate change impacts on the two specific energy systems will be done in a backward way, representing the information and trends in an effect-and-cause approach.

8.2.1 Impacts on water

Looking at Figure 8.1 which represents the paths of climate impacts on an energy system, we could note that climate change, temperature changes and precipitation changes are the origins of the changes of the water system.

The following description will concentrate on the alterations of water resource by these causes: we will refer to the cryosphere, evaporation, sea level, extreme events like floods and droughts, streamflows and salinity.

8.2.1.1 Climate change's impacts on water

Climate change substantially modifies some aspects of the water system, which are the cryosphere and the evaporation.

The cryosphere is composed by various elements set by different forms of water. Snow ice, snow cover and permafrost constitute the cryosphere: therefore, these elements are those affected by climate change in general

For its latitude, Spain does not present large areas where ice or snow could last for long time. The only one is the Pyrenees region. Nevertheless, according to *21st century climate change in the European Alps—A review* (Gobiet et al., 2014), the Pyrenees have lost almost 90% of their glacier ice and the rest may disappear within a few decades. The information in the Climate Adaptation website agree with this sentence. It says further that snow cover on mountains will probably be less in the future because, in most temperate mountain regions, the snow temperature is close to the melting point and is very sensitive to changes in temperature.

Italy contains a large mountain chain, the Alps, where ice and snow could last much more than in Spain. Gobiet et al. (2014) estimated the disappearance of the smaller glaciers by 2050 and the reduction of glacier cover by 80% by the end of the 21st century if temperature will rise about 3°C. According to other sources in the website, snow cover will almost not last under 1000m with a rise of +4°C and water in general will decrease up to -80% by 2100 at 2500m. Summarizing, glacier and snow are likely to disappear in this area.

The evaporation of water fundamentally increases if the temperature of air increase. Spain and Italy will be countries that will massively suffer from this situation. The Working Group II of the IPCC in the Fifth Assessment Report (IPCC, 2014) summarized the future projections of water content jointly for Spain and Italy. Soil water content will decline; groundwater recharge and water table level would be significantly reduced by the end of the 21st century for river basins. Gobiet et al. (2014) focused onto the changes in relative humidity, declaring that in winter it will increase very little, whereas in summer it will decrease by more points. Even the report *Climate change and the Mediterranean region* (Karas, 1997), composed for

Greenpeace, concentrated on the moisture problem, explaining that soil moisture in southern Europe will decrease to -25% during summer.

8.2.1.2 Impacts of temperature changes on water

As already said, an evident consequence of climate change is the increase of temperatures of air and water resources. These increases provoke a correlated effect in the water system, especially in oceans and seas: the sea level is rising.
There are two mechanisms that lead to the rise of sea level: one is the heat expansion and the other is the ice melting. These mechanisms are ultimately caused by the increase of temperatures. In the Fifth Assessment Report (IPCC, 2013) the authors distinguished the two different mechanisms of rising when they referred to the Global Mean Sea Level, supplying detailed data and trends about them. When they referred to Europe they did not distinguish the trends, giving only overall ranges. They projected a rise of sea level in a range from +30cm to +80cm, depending on the chosen scenario.
According to the European Environment Agency (2012), by the end of 21st century the Mediterranean sea will undergo an increase between +3 and +61 cm over the basin; instead, in accordance with IDDRI (2009), the rise will be higher since they projected an increase between +18 and +59 cm. Then the Met Office in *Climate: Observations, projections and impacts – Spain* (Met Office, 2011a) and *Climate: Observations, projections and impacts – Italy* (Met Office, 2011b) reported almost the same ranges of the IDDRI's study, giving more details about the different climate scenarios.

8.2.1.3 Impacts of precipitation changes on water

Changes in precipitation patterns lead to several different events related with water. These events are floods, droughts, changes in freshwater resources and changes in salinity.

As regards floods, there is no extreme certainty about future projections because they remarkably depend on precipitation patterns though they depend on other non-climatic factor like soil characteristics. Nevertheless, the Met Office, in its two reports about Spain and Italy, stated that in Spain uncertainty remains over extreme short-term precipitation and the associated pluvial flooding, whereas for Italy they suggested an increase in extreme flood levels across the country and a reduction in average annual flow. In *21st century climate change in the European Alps—A review* (Gobiet et al., 2014), the authors declared that the most important winter flood in a century could be 5 times more frequent, becoming a 20 years event, assuming a +10% of precipitation. Other studies indicated in the Climate Adaptation website strengthened this last statement, but they also added that future flood risk in Italy is not univocal because different projections supply different trend, positive and negative. For Spain they said that, in those areas like Pyrenees where snowmelt floods are dominating, extreme floods will decrease. They continued adding that flood hazard instead will increase during wetter and warmer winters when there will be more frequent rain and less frequent snow.

Drought events have been studied by several research groups. For Gobiet et al. (2014) at the end of the century droughts events will be little more frequent, but the intensity will grow as the average duration. The Met Office (2011a) indicated that droughts in Spain could increase in frequency and magnitude, with the greatest impacts projected for the south of the country, along the Mediterranean coast. They reported also the projections of *Climatic changes and associated impacts in the Mediterranean resulting from a 2 °C global warming* (Giannakopoulos et al., 2009)*,* which expressed that the number of dry days will increase to the order of 3-4 weeks during the 2031-2060 time horizon, and the longest dry spell will increase under a 2°C warming scenario. For Italy the Met Office (2011b) affirmed that droughts could increase in frequency and magnitude with climate change for the country as a whole. Recent droughts events highlighted that the north is susceptible to severe episodes: several national-scale studies agreed that the south is highly vulnerable to water stress and the number of dry days (days with daily precipitation less than 0.5mm) will increase.

Freshwater resources include water in rivers, lakes and aquifers. The Climate Adaptation website ("Home - Climate Adaptation," n.d.) shows data and trends about Spain and Italy. Spain will see a reduction of general freshwater resource from 5 to 14% by 2030, 17% by 2060 and 22% by 2100. By the 2050 the potential groundwater recharge will decrease of about 70%, the water resource in the Pyrenees will diminish up to 20% and in the Ebro valley to 35% by 2050. For Italy they stated that in general groundwater recharge will decline up to 30% by 2050.

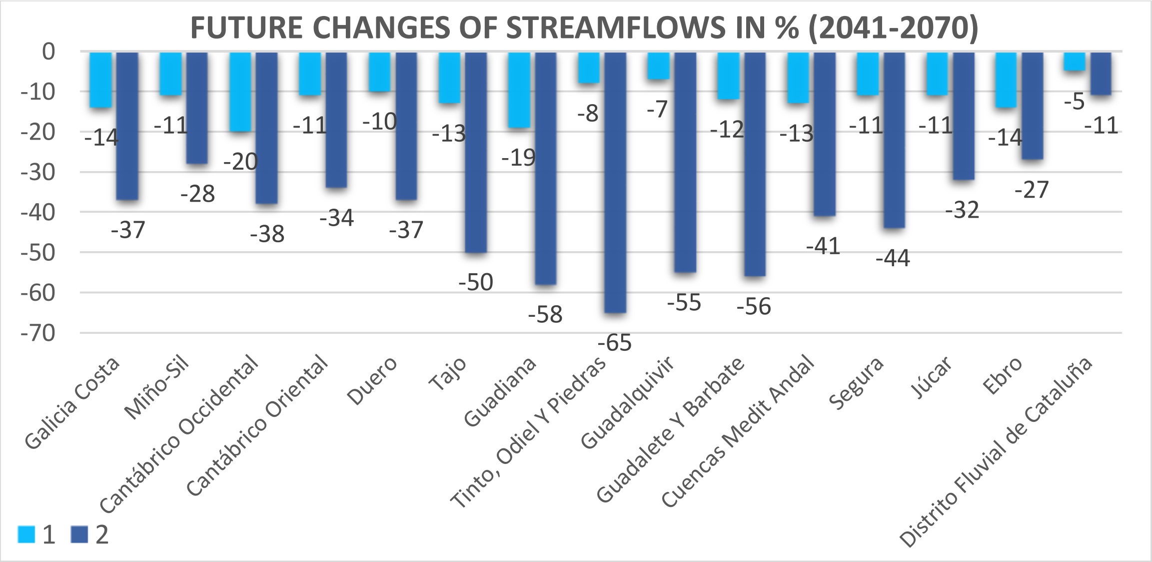

Figure 8.2 Future changes in resource availability in percentage. Data collected from (Instituto de Investigación Tecnológica, 2015, p.36)

The report *Nuevas tecnologías de generación eléctrica a partir de la disponibilidad de recursos hídricos en enscenarios de cambio climático. Informe final* (Instituto de Investigación Tecnológica, 2015) provided specific regional data about the future change of available water resource. They supplied percentages of changes of two different scenarios (1 and 2) which are a medium and a strict climate change scenario. Figure 8.2 shows the trends for the period 2041-2070.

Salinization occurs essentially near the coasts: freshwater inland resources can be contaminated to the intrusion of saline water, both underground and on surface. Salinization depends on various factors, climatic and non-climatic. The reduction of freshwater resources due to decrease of precipitation is one of the most impacted change. In Spain, according to ("Home - Climate Adaptation," n.d.), salinization will occur in coastal aquifers due to sea level rise and aquifer depletion. In Italy, along the Adriatic and Mediterranean, problems of saline intrusion will be exacerbated by reductions in runoff.

8.2.2 Impacts on energy resources

All those sources that may be used to generate electricity are here considered as energy resources. We can divide them into two great groups: renewable and non-renewable resources. The focus is aimed at the energy endowment, i.e. the amount of primary energy available for every resource.

In this section we consider that energy resources could be impacted by two agents as we can see in Figure 8.1, climate change and water. Actually, energy resources could be affected by more elements, as temperature, precipitation, water, energy and atmospheric circulation. But, to simplify the description, we aggregate the climatic consequences which affect the energy endowment under a unique parameter: the climate change. For hydropower endowment we do an exception: we consider it affected only by water system, to make visible the strong correlation between the water and the energy systems.

8.2.2.1 Climate change's impacts on energy resources

The resources that we consider influenced by climate change are renewable and non-renewable, and are wind, biomass, wave and tidal and fossil fuel. Following, we will concentrate only on wind energy and biomass energy because wave and tidal energy and fossil fuels are not so common in the countries we are taking in consideration.

Talking about wind potential, in the near term in Spain and Italy there are no significant changes expected. In accordance with the Working Group II of IPCC (Field, 2014), after 2050 a decrease in wind energy is expected in winter and summer in the south of Europe, except for the Adriatic coast, where a significant increase during summer is possible. Gaudioso in *L'impatto dei cambiamenti climatici sul sistema energetico italiano: verso una strategia nazionale di adattamento* (Gaudioso, 2012) suggested that air density could be reduced in winter in southern Europe by the end of the century, adding that it could be negligible compared to climate variability.

The biomass crop for energy use has been rather studied, focusing on the growth rate of yields and the suitable areas for growing biofuels crops.

In the report *Impacts and adaptation of European crop production systems to climate change* (Olesen et al., 2011) it is affirmed that a reduction of crop yields is expected around the Mediterranean. In southern Europe, in particular, a decrease of spring-sown crops (maize, sunflower and soybeans) is expected. For autumn-sown crops (winter and spring-wheat), a strongly decrease of the yield is expected in the southern areas, except of the cooler areas like the north of Spain.

In *The potential distribution of bioenergy crops in Europe under present and future climate* (Tuck et al., 2006), the authors projected a dramatic decline of the potential distribution of the studied bioenergy crops by the 2080s in Spain due to increased droughts. For Italy, they indicated as causes of the reduction of the yield of summer crops like sunflowers and soybeans the increase in the frequency of extreme climate events during specific crop development stages together with higher rainfall intensity and longer dry spells. For Spain and Italy in general, they projected a reduction of the 15% of the potential area for growing biofuel crops like oilseed rape, sunflower, sugarcane and maize.

8.2.2.2 Impacts of water changes on energy resources

The changes in the water sector produce an alteration of the hydropower endowment, which we could observe and weight looking at the changes in runoff.

In the Climate Adaptation website this impact is well expanded. It is stated that in general the runoff will decrease. Summer flows may be reduced by up to 80% in some rivers in southern Europe. There could be a decrease of 23% of runoff by 2020s and a reduction of 36% by 2070s. They continued saying that an increase of winter runoff and a decrease of spring runoff is possible and could be change the reservoirs' management strategies.

Two Spanish technical reports (*Estudio de los impactos del cambio climático en los recursos hídricos y las masas de agua. Ficha 1: evaluación del impacto del cambio climático en los recursos hídricos en régimen natural* (CEDEX, 2010) and *Estudio de los impactos del cambio climático en los recursos hídricos y las masas de agua. Efecto del cambio climático en los recursos hídricos disponibles en los sistemas de explotación* (CEDEX, 2012)) communicated respectively the future expected changes in runoff and the changes in global water resource for energy use, indicating a reduction of 28% of runoff by 2100 and a reduction of the 34%

of water resource by 2100. Then the report *Nuevas tecnologías de generación eléctrica a partir de la disponibilidad de recursos hídricos en enscenarios de cambio climático. Informe final* (Instituto de Investigación Tecnológica, 2015), which supplied data from the two CEDEX technical reports, provided future regional changes of runoff for two climate change scenarios, which are expressed in Figure 8.3.

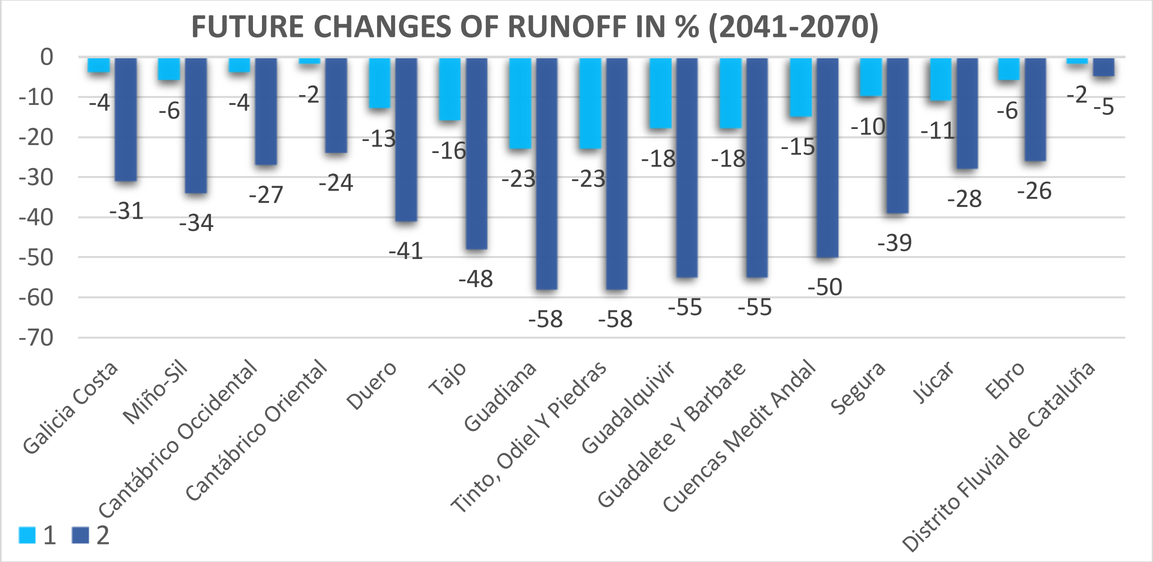

Figure 8.3 Future changes of runoff in percentage. Data collected from (Instituto de Investigación Tecnológica, 2015, p.36)

Specific studies, examined by the Climate Adaptation website, analyzed specific Italian regions. Central Alps, for example, are projected to experience a +90% of winter runoff in the future and a -45% of summer runoff. The Crati river basin then will suffer a reduction of the 40% of water by 2100.

8.2.3 Impacts on energy demand

The demand of energy is strongly affected by the changing climate. The evaluation of impacts and modification of energy demand is necessary for the management of the entire energy system and for the adaption of it to climate change.

Climate change in general provokes the modifications, but specifically the changes in temperature and the changes in the water sector are the origins of these alterations. There will be a strong alteration in the heating and cooling demand in buildings, in the energy and water demand for industrial processes and for agriculture, and also in the demand of energy for water treatment for domestic use.

In literature there are not so many documents which regard future impacts of climate change on energy demand in Spain and Italy. The general trends are known but specific data about these countries are missing. There is no information about the changes in industry energy demand, neither about the changes in energy use for water treatment. Anyway, it is possible to give some facts about them.

As regards heating and cooling demand in buildings, some projections are available. As mentioned by Gaudioso (2012), in the residential and tertiary sectors, with the rise of air temperatures, energy demand for heating purpose will decrease, whereas energy demand for cooling will increase. The magnitude of these modifications could vary depending on the season and region. Spain and Italy, which are located in the south of Europe, will experience a higher increase of maximum temperatures than minimum temperatures. Furthermore, the efficiency of cooling systems is lower than the efficiency of heating systems. These aspects lead to an increase of energy demand for cooling higher than the decrease of energy demand for heating. In the Climate Adaptation website, they talk about an increase of 50% of electricity consumption by 2080 in Italy and Spain (World Health Organization, 2007, *Environment and health risks from climate change and variability in Italy*), and an increase of 114% by 2070 for cooling only for Madrid (Parry and Intergovernmental Panel on Climate Change, 2007).

Most of the energy used in industry is utilized for water heating. Climate change, which will rise the temperature of water resources, would likely reduce the use of energy in industry. But the use of water in industry will not decrease as the use of energy: on the contrary, it will rise for climate change.
Concerning agriculture, the paper *Water: A key resource in energy production* (Rio Carrillo and Frei, 2009) declared that the 2030 projected Spain energy mix tends to be more water consumptive. This fact is due to the increase of use of biomasses, which are water intensive. This increase will be attested to +25%.

The energy and water requirements to supply freshwater resources in Spain and Italy (but also in the world in general) have not been projected.

8.2.4 Impacts on energy supply

This section of the assessment of climate impacts on an energy system is the main one section. It concentrates on the impacts of climate change on the supply side of the energy system, which provides the necessary amount of energy for the comprehensive utilization.

As we can see from Figure 8.1, energy supply could be affected by 5 parameters: temperature, water, extreme events, energy resources and climate change. Three connections out of five indicate a specific aspect of the energy supply system which is impacted by climate change. Temperature's impacts refer to the changes in the efficiency of energy supply. Water's impacts refer to the changes in refrigeration. Instead, climate change impacts treat the mitigation projections in energy generation.

Even in this case there are not so many available data about all these changing aspects, especially with regard to the changes by extreme events. It is difficult to predict extreme events like floods, droughts, gusts of wind, extreme temperature, extreme precipitations and hurricanes. This complication does not permit to find precise changes in the supply. For these alterations we refer to what we wrote in the general case.

8.2.4.1 Impacts of energy resource changes on energy supply

The energy resources we take in consideration for this analysis are water for hydroelectric production, wind for wind generation, biomass for biofuels or thermal production and solar energy for photovoltaic or solar panels.

About hydropower production, in the long term the reduction of water resource, predicted in the south of Europe, will imply a decrease of hydroelectricity production and an increase attention on the variability of water flows across the seasons. The Working Group II of the IPCC in *Climate change 2014: impacts, adaptation, and vulnerability. Part B, Regional aspects* (Field, 2014) predicted a decrease of 5-15% of electricity production in southern Europe in 2050. The projections for Alps' generation are not better: the electricity production will decrease up to 36% by 2100. In general, the hydropower potential is predicted to diminish of about 50% in the Mediterranean Sea region by 2070.

For wind, biomass and solar energy, as for water energy, the matter is always the same. The supply of electricity from these renewable resources depends on the availability of the resources themselves. The focus of this section is the assessment of the changes in energy production due to changes of resource availability. So, electricity production will vary proportionally to the amount of the resource.
Wind resource will probably not change in the near future and consequently wind generation will not vary so much. Biomasses will decrease and, as results, the energy generation. Solar radiation will not vary, so the generation of energy from sun will not change due to solar energy changes.

Regarding the impact of climate change on plants' operation, Gaudioso (2012) said that the projected impacts on wind turbines, biomass installations, photovoltaic and thermal solar panels will be so small that they could be ignored for ordinary management and also for long-term strategies. Climate variability will have a higher influence than climate change in the operation of these plants.

8.2.4.2 Impacts of temperature changes on energy supply

As already said, the focal point of this segment is the efficiency of generation devices due to temperature changes. The analysis will concentrate on the efficiency of thermal and photovoltaic panels, thermal pants and the transmission and distribution grids.

As stated by Gaudioso (2012), the efficiency of solar cells in the Mediterranean area will be reduced of about 1% with an increase of 2°C of air temperature. This effect will be compensated by an increase of solar radiation (due to less cloudiness) which increases cells' performance. In the Climate Adaptation website ("Home - Climate Adaptation," n.d.) it is reported that PV output is likely to increase by a few percent in Europe.

About thermal plants and their efficiency, the changes depend on air temperature and water availability projections for the countries and on the type of thermal cycle used in the plants. The decline of efficiency, due to these aspects, is described in the general analysis and we will not focus more on that. What most concerns us is the summer average usable capacity of a thermal plant. Future increased temperatures will not allow to release huge amounts of heat energy due to environmental limitation: this leads to a decrease of usable capacity of a plant from 6 to 19% by 2031-2060 compared to 1971-2000 (Field, 2014, p.1282)

The transmission and distribution grids are expected to suffer temperature increases. The rise of temperatures causes an increase of electric cables' resistance and consequently an increase of transmission losses, because it makes difficult the dissipation of the generated heat.

8.2.4.3 Impacts of water changes on energy supply

This part concentrates on the refrigeration systems, especially of thermal plants.
Thermal power cycles usually have a cooling system that uses water as refrigerant. The increase of air and water temperatures leads to an increase of water withdrawal or water consumption (depending on the type of cooling system) to refrigerate the plant. Recalling the information of the general chapter, a 1°C increase in water temperature reduces power output by 0.45%.
In a study over Spain done by Rio Carrillo and Frei (2009), the withdraw and consumption of water for electricity generation is projected to decrease by 2030, due to a change in energy generation mixing. In the report *Nuevas tecnologías de generación eléctrica a partir de la disponibilidad de recursos hídricos en enscenarios de cambio climático. Informe final* (Instituto de Investigación Tecnológica, 2015) the authors defined the withdraw and consumption of water for energy generation in2050 in specific river basins for four different climate change scenarios. The data are reported in Table 8.1.

Table 8.1 2050 water consumption and withdraw in hm^3 in Spain's river basins (Instituto de Investigación Tecnológica, 2015, p.47-49)

BASIN	WC1na		WC2na		WC1ca		WC2ca	
	CONS	WITH	CONS	WITH	CONS	WITH	CONS	WITH
GALICIA COSTA	173	1.163	243	1.120	127	2.149	131	1.889
MIÑO SIL	230	2.891	219	2.197	469	5.441	360	4.727
CANTÁBRICO OCC	157	1.131	224	1.524	128	2.380	202	2.455
CANTÁBRICO OR	181	334	86	432	127	1.650	110	3.055
DUERO	349	5.896	277	4.877	257	5.280	323	7.685
TAJO	349	7.617	468	7.548	341	6.368	279	4.887
GUADIANA	140	1.269	96	767	150	3.240	105	2.970
TINTO, ODIEL Y PIEDRAS	58	327	39	232	61	1.337	52	417
GUADALQUIVIR	0	0	0	0	0	0	0	0
GUADALETE Y BARBATE	0	0	0	0	0	0	0	0
MEDITER ANDAL	0	0	0	0	0	0	0	0
SEGURA	0	0	0	0	0	0	0	0
JÚCAR	169	4.624	128	3.565	120	3.355	114	1.761
EBRO	303	9.844	301	9.497	305	5.273	363	4.410
CATALUÑA	168	3.205	118	3.215	211	2.656	177	1.705

Note. WC1na: medium climate change scenario without adaptation. WC2na: strict climate change scenario without adaptation. WC1ca: medium climate change scenario with adaptation. WC2ca: strict climate change scenario with adaptation

8.2.4.4 Impacts of climate change mitigation on energy supply

This section regards the countries' strategies to reduce the GHG emissions from energy supply. The solution is quite simple: energy production from fossil fuels must be reduced whereas energy production with no-CO_2 generation facilities must increase. The objective must be to convert the actual fossil fuel based system to a renewable energy based energy system.

In Europe every country has to participate to the effort of reducing GHG emissions, implementing specific strategies to reach this objective. The purpose of this section is not to explain in detail the Spanish and Italian strategies, but only to give an account of them.
With the Directive 2009/29/CE, the European Union set the so called "20-20-20 Targets": the objectives were to reduce the emission of greenhouse gases of the 20% in 2020 relative to the 1990 level, to generate the 20% of the energy requirements with renewable sources and to increase the energy efficiency of a 20%. The European Council then formulated another strategy: on 24th October 2014 it approved the *EUCO 169/14* (European Council, 2014) in which it endorsed a binding EU target of an at least 40% domestic reduction in greenhouse gas emissions by 2030 compared to 1990. They highlighted that the target will be delivered collectively by the EU in the most cost-effective manner possible, with the reductions in the Emission Trading System and non-Emission Trading System sectors amounting to 43% and 30% by 2030 compared to 2005 respectively. They also added that all Member States will

participate in this effort, balancing considerations of fairness and solidarity. This substantially means that all European countries, Spain and Italy included, must implement future mitigation strategies to reach the goal of at least 40% domestic reduction in GHG emissions by 2030. Even if the Directive treats domestic energy use, this target extends to the whole energy system.

CHAPTER 9

CASE STUDY'S SUMMARY TABLES

In this last part of the case study, we will make a recap of what has been commented about the energy systems of Spain and Italy and about the climate impacts in the countries. We will compose specific summary tables about the vulnerabilities and climates changes that could be found in the two aforementioned energy systems. Then, we will end the analysis summarizing the possible adaptation options we can implement in the countries, using once again a summary table.

The tables about Spain and Italy will be modeled from the general summary tables inserted through the thesis. Fundamentally, we will compare the vulnerabilities of the two examined energy systems, the impacts of climate change on the countries and the adaptation measures to the systems with the findings of the general analysis.

Table 9.1 recaps the vulnerabilities of the Spanish and Italian energy systems. This table presents a distinctive characteristic. Differently from the summary table about general vulnerabilities, this one does not only indicate the vulnerabilities of the two systems, but it also points out the magnitude of them. A four-levels scale will state the extent of the vulnerability: the levels will be no, low, medium and high. The aim of this codification is to specify the degree of vulnerability of the components of our case study's energy systems to choose the best adaptation measures for the systems.

Tables 9.2 and 9.3 summarize the climate change's impacts, respectively in Spain and Italy. These tables are filled by specific data, ranges and trends about the impacts in the two countries, even more specific than the general trends recounted in Chapter 8.

Table 9.4 finally sums up the possible adaptation measures we can implement in our countries' energy systems. The feasible measures are determined by the climate impacts, the vulnerabilities and their magnitude on each part of the system. We will use checkmarks and x marks to state if a precise adaptation measure is suitable or not in our energy systems.

Table 9.1 Vulnerabilities of the Spanish and Italian energy systems to climate change

ENERGY SECTOR	VULNERABILITY	SPAIN	ITALY	CORRELATED VULNERABILITY	SPAIN	ITALY
HYDROPOWER	Water resource availability	MEDIUM	LOW	Quantity of runoff and seasonal high and low flows Temperature Precipitation Evaporation Extreme events	MEDIUM HIGH MEDIUM MEDIUM MEDIUM	MEDIUM HIGH MEDIUM LOW LOW
	Reservoir storage	LOW	LOW			
	Dependency: glacier – precipitation - runoff	MEDIUM	MEDIUM			
	Infrastructure safety	LOW	LOW	Floods Droughts Glacial Lake Outburst Flood (GLOF)	MEDIUM HIGH NO	HIGH HIGH NO
WIND POWER	Large dependence on variations in wind patterns	MEDIUM	-	Impossibility to make adequate predictions of wind characteristics	MEDIUM	-
	Wind characteristics and patterns	MEDIUM	HIGH	Carbon dioxide emissions Rise of temperatures Changes in vegetation Air density	- LOW - -	- LOW - -
	Impossibility of storage	HIGH	HIGH			
	Infrastructure safety	LOW	LOW	Hurricanes Sea level rise (offshore) Icing	NO LOW NO	NO MEDIUM LOW
SOLAR POWER	Photovoltaic cell temperature	NO	NO	Irradiance Wind cooling Ambient temperature	- - MEDIUM	- - MEDIUM
BIOMASS AND BIOFUELS	Biomass resource availability	LOW	NO	Temperature Precipitation Atmospheric concentration of CO_2 Extreme events: droughts, frosts, hurricanes	LOW LOW - MEDIUM	LOW LOW - MEDIUM
	Use in thermal plants and biofuel production	MEDIUM	MEDIUM	Rise of temperatures Complexity in maintaining a constant temperature Water availability Water properties	LOW LOW HIGH HIGH	LOW LOW HIGH HIGH
WAVE AND TIDAL ENERGY	Availability of wind	-	-			
	Large dependence on variations in wind patterns	-	-			
	Wind characteristics and patterns	-	-	Carbon dioxide emissions Rise of temperatures Changes in vegetation Air density	- - - -	- - - -
	Infrastructure safety	-	-	Sea level rise	-	-

THERMOELECTRIC POWER PLANTS	THERMAL CYCLE EFFICIENCY Increase of ambient air temperature Increase in water temperatures	MEDIUM MEDIUM	MEDIUM MEDIUM	Location of water intake, location of outlet, fluid velocities, turbulence, pressure changes	-	-
	COOLING SYSTEM Water availability Water characteristics Type (once-through/recirculating) Carbon Capture and Storage (CCS)	LOW LOW - -	LOW LOW - -	Once-through cooling system: streamflow condition Recirculating cooling system: water consumption Location of the cooling water intake	MEDIUM MEDIUM -	MEDIUM MEDIUM -
	INFRASTRUCTURES Safety Site of building Safety function of safety-related structure	LOW - -	LOW - -	Climate change and extreme events Air and sea temperatures, Wind, Precipitation, Flow rate of rivers, Sea level, Storms	LOW	LOW
FOSSIL FUEL	Infrastructure safety	-	-	Sea level rise, Storm intensity, Wave regime, Air and water temperature, Precipitation pattern, CO_2 concentrations, Ocean acidity, Permafrost thawing	-	-
	Efficiency of equipment	-	-	Rise of temperatures Water availability	-	-
ENERGY TRANSFER	Efficiency of transmission lines and transformers	MEDIUM	MEDIUM	Rise of temperatures Extreme events, in particular icing and lightning Permafrost thawing	MEDIUM LOW -	MEDIUM LOW LOW
	Infrastructure safety	LOW	LOW			
	Pipelines	LOW	LOW	Climate phenomena Soil structure Erosion Subsidence	LOW - - -	LOW - - -
	Pumping stations and valves	-	-			
	Means of transport	-	-	Floods Water levels Droughts	- - -	- - -

Note. This evaluation is personal, and it is based on the information collected about climate change and its impacts on Spanish and Italian energy systems. The levels of vulnerability were subdivided into no, low, medium and high. The sign (-) stands for the impossibility to give an evaluation due to limited information

Table 9.2 Summary specific table of climate change and its impacts on the energy system in Spain

SPAIN’S IMPACTS			PROJECTIONS / TRENDS	REFERENCE
CLIMATE CHANGE	TEMPERATURE	GMST	Projections period: 2071-2100. Reference period: 1971-2000 South: +2.0°C [1.9 to 3.2] (RCP4.5) +4.2°C [3.8 to 5.7] (RCP8.5) Atlantic: +1.7 [1.3 to 2.9] (RCP4.5) +3.2 [2.5 to 4.2] (RCP8.5)	(Jacob et al., 2014)
			+0.4°C/decade in winter. +0.7°C/decade in summer Hinterland: +5-7°C in winter +3-4°C in summer by 2100	(“Home - Climate Adaptation,” n.d.)
		OCEAN	+2°C (21.7°C) by 2100	(IDDRI, 2009)
		WATER	Reference period: 1971-2000 +0.8 to +1.0°C for 2031-2060. +1.4 to 2.3°C for 2071-2100	(“Home - Climate Adaptation,” n.d.)
	PRECIPITATION	PRECIPITATION PATTERN	Projections period: 2071-2100. Reference period: 1971-2000 South: -6% [-11 to 2] (RCP4.5) -10% [-27 to 0] (RCP8.5) Atlantic: +1% [-1 to 9] (RCP4.5) +4% [-2 to 9] (RCP8.5)	(Jacob et al., 2014)
			2011-2040: -5% in central, N and E. -10% in SW 2070-2100: -15%-25% in central and N. -20%-30% in S 2100: -6%-14% Andalucia and Cataluña. +14% French border 2050: -20% in summer -30% in winter in the Pyrenees	(“Home - Climate Adaptation,” n.d.)
	EXTREME EVENTS	TEMPERATURE	Projections period: 2071-2100. Reference period: 1971-2000 Warm days per year: +34 [28 to 83] (RCP4.5) +124 [90 to 186](RCP8.5) Cold days per year: -5 [-3 to -6] (RCP4.5) -5 [-3 to -6] (RCP8.5)	(Jacob et al., 2014)
			Basque Country: -50% frost days by 2100 Cold-wave episodes: disappear beyond 2020 Heat waves. Number of summer days. 16% by 2050 22% by 2100	(“Home - Climate Adaptation,” n.d.)
		PRECIPITATION	Projections period: 2071-2100. Reference period: 1971-2000 South: +36% [23 to 62] (RCP4.5) +49% [30 to 65] (RCP8.5) Atlantic: +36% [20 to 73] (RCP4.5) +71% [48 to 118] (RCP8.5)	(Jacob et al., 2014)
		ATMOSPHERIC CIRCULATION	Projections period: 2071-2100. Reference period: 1961-2000 Relative changes of mean annual storm loss potential	(van der Linden and Mitchell, 2009)
			+2-4% maximum wind speeds in NW by 2100 Tropical hurricanes might become a serious threat for Western EU	(“Home - Climate Adaptation,” n.d.)
WATER	CLIMATE CHANGE	CRYOSPHERE	Snow cover will probably be less in the future Pyrenees: 90% of glacier ice already lost. The rest may disappear within few decades	(“Home - Climate Adaptation,” n.d.)
		EVAPORATION	-15% to -25% soil moisture during summer	(Karas, 1997)
			+15 to +20% evapotranspiration until 2100	(“Home - Climate Adaptation,” n.d.)
	TEMPERATURE	SEA LEVEL	Projections period: 2081-2100. Reference period: 1986-2005 +0.29 to 0.55 (RCP2.6) +0.36 to 0.63 (RCP4.5) +0.37 to 0.64 (RCP6.0) +0.48 to 0.82 (RCP8.5)	(Field, 2014)
			Atlantic coast: +15cm by 2050. +50 to +100cm by 2100	(“Home - Climate Adaptation,” n.d.)
			Mediterranean sea: +18 to +59cm by 2100	(IDDRI, 2009)
	PRECIPITATION	FLOODS	The most important winter flood: 5 times more frequent	(Gobiet et al., 2014)
		DROUGHTS	Projections period: 2071-2100. Reference period: 1971-2000 +4.7% (B1) / 4.7% (A2) number of drought events +89.9% (B1) / +143.1% (A2) average duration +375.2% (B1) / +467.4% (A2) average deficit volume	(Gobiet et al., 2014)
		STREAMFLOWS	-5% to -14% by 2030 -17% by 2060 -20% to -22% by 2100 -70% potential groundwater recharge by the 2050s -15% to -20% water resources in Pyrenees by 2050 -25% to -35% water resources in Ebro Valley by 2050	(“Home - Climate Adaptation,” n.d.)
			Water resources. Reference period: 1961-1990 -16% (A2) / -21% (B2) 2011-2040 -23% (A2) / -19% (B2) 2040-2070 -34% (A2) / -20% (B2) 2071-2100	(CEDEX, 2010)

ENERGY RESOURCES	CLIMATE CHANGE	WIND	Before 2050: no significant changes After 2050: decrease in wind energy in winter and summer	(Field, 2014)
		BIOENERGY	% of total land suitable are for growing biofuel crops Oilseed rape: 70% (1990) -5-15% (2020-2050-2080) Sugarcane: 10% (1990) -5-15% (2020-2050-2080) Maize: 75% (1990) -5-15% (2020-2050-2080)	(Tuck et al., 2006)
	WATER	RUNOFF	Reference period: 1971-2000 -13% to -15% for 2031-2060. -16% to -23% for 2071-2100 Increase in winter runoff, decrease of spring runoff	(“Home - Climate Adaptation,” n.d.)
			Runoff: Reference period: 1961-1990 -8% (A2) / -8% (B2) 2011-2040 -16% (A2) / -11% (B2) 2040-2070 -28% (A2) / -14% (B2) 2071-2100	(CEDEX, 2010)
ENERGY DEMAND	TEMPERATURE	HEATING DEMAND	-10% energy requirements by 2030	(“Home - Climate Adaptation,” n.d.)
			Reference: no climate change scenario Cold/wet scenario: -9% in 2030 / -19% in 2050 / -9% in 2010-2050 Average scenario: -8% in 2030 / -19% in 2050 / -8% in 2010-2050 Warm/dry scenario: -16% in 2030 / -28% in 2050 / -16% in 2010-2050 Emissions reduction: -14% in 2030 / -9% in 2050 / -9% in 2010-2050	(Dowling, 2013)
		COOLING DEMAND	+50% electricity demand by 2080s +114% electricity demand for Madrid by 2070s	(“Home - Climate Adaptation,” n.d.)
			Reference: no climate change scenario Cold/wet scenario: 17% in 2030 / 39% in 2050 / 14% in 2010-2050 Average scenario: 25% in 2030 / 52% in 2050 / 22% in 2010-2050 Warm/dry scenario: 28% in 2030 / 66% in 2050 / 30% in 2010-2050 Emissions reduction: 27% in 2030 / 38% in 2050 / 28% in 2010-2050	(Dowling, 2013)
		AGRICULTURE	-70mm/year of net irrigation requirement in the 2020s for W Spain	(Field, 2014)
ENERGY SUPPLY	TEMPERATURE	EFFICIENCY		
		• SOLAR POWER	PV output from 2010 to 2080 is likely to increase by a few percent CSP is likely to increase by more than 10%	(“Home - Climate Adaptation,” n.d.)
		• THERMAL PLANTS	+1°C monthly ambient temperature (Nuclear power supply) -0.7% production (near 0°C) -2.3% production (near	(“Home - Climate Adaptation,” n.d.)
	WATER	REFRIGERATION	Projections period: 2031-2060. Reference period: 1971-2000 -6% to -19% summer average usable capacity	(Field, 2014)
	ENERGY RESOURCES	HYDROPOWER	-5% to -15% electricity production (2050 compared to 2005)	(Field, 2014)
			-1.82% TWh by 2050 (-1.79TWh, reaching 96.60 TWh)	(Hamududu and Killingtveit, 2012)
		WIND	The potential for wind energy under climate change will probably not increase	(“Home - Climate Adaptation,” n.d.)
		BIOFUEL	+400% water consumption by 2030 (Scenario: Reference Mix) +1600% water consumption by 2030 (Scenario: Biofuels Mix)	(Rio Carrillo and Frei, 2009)
	CLIMATE CHANGE	MITIGATION	-40% domestic reduction in GHG by 2030 compared to 1990	(European Council, 2014)

Table 9.3 Summary specific table of climate change and its impacts on the energy system in Italy

ITALY’S IMPACTS			PROJECTIONS / TRENDS	REFERENCE
CLIMATE CHANGE	TEMPERATURE	GMST	Projections period: 2071-2100. Reference period: 1971-2000 Alpine region: +2.4°C [1.8 to 3.6] (RCP4.5) +4.6°C [3.8 to 6.3] (RCP8.5)	(Jacob et al., 2014)
			+1.2°C spring / +1.6°C summer and winter by 2050 +2.7°C spring / +3.8°C summer by 2100	(Gobiet et al., 2014)
			Reference period: 1961-1990 +1.5°C to 2.0°C for 2021-2050 (up to +3.0 for summer, autumn, spring) +2.5°C for 2070-2099 during winter, spring and autumn +3.5°C to +4.0°C for 2070-2099 during summer	(“Home - Climate Adaptation,” n.d.)
		OCEAN	Adriatic Sea: +2.5°C (20.2°C) by 2100	(IDDRI, 2009)
		WATER	Reference period: 1971-2000 +0.8 to +1.0°C for 2031-2060. +1.4 to 2.3°C for 2071-2100	(“Home - Climate Adaptation,” n.d.)
	PRECIPITATION	PRECIPITATION PATTERN	Projections period: 2071-2100. Reference period: 1971-2000 Alpine region: +5% [3 to 12] (RCP4.5) +14% [5 to 18] (RCP8.5)	(Jacob et al., 2014)
			-4.1% in summer / +36% in winter by 2050 -20.4% in summer / +10.4 in winter by 2100	(Gobiet et al., 2014)
			Northern parts of Mediterranean sea: wetter. Southern parts: drier -10 to -40% in summer precipitation	(“Home - Climate Adaptation,” n.d.)
	EXTREME EVENTS	TEMPERATURE	Projections period: 2071-2100. Reference period: 1971-2000 Warm days per year: +34 [26 to 69] (RCP4.5) +96 [73 to 162] (RCP8.5) Cold days per year: -5 [-3 to -7] (RCP4.5) -5 [-3 to -6] (RCP8.5) 2100: 1 summer in 2 as hot as 2003 summer 2100: 6 winters in 10 as hot as record 2006-2007 2100: 7 springs in 10 as hot as record 2007 2100: 6 autumns in 10 as hot as 2006 autumn	(Jacob et al., 2014)
			Projections period: 2031-2060. Reference period: 1961-1990 Hot days. 2 weeks along the coast / 5-6 weeks inland Tropical nights. 4 weeks everywhere Heat wave day.3-5 weeks everywhere Frost days. -35 day in 2070-2099	(“Home - Climate Adaptation,” n.d.)
		PRECIPITATION	Projections period: 2071-2100. Reference period: 1971-2000 Alpine region: +38% [24 to 7] (RCP4.5) +79% [41 to 119] (RCP8.5)	(Jacob et al., 2014)
		ATMOSPHERIC CIRCULATION	Future declines in extreme wave height in the Mediterranean Sea	(“Home - Climate Adaptation,” n.d.)
WATER	CLIMATE CHANGE	CRYOSPHERE	Rule of thumb: average level of snowline rises by roughly 150m/°C +2-4°C snowline shifts by 300-600m by 2100	(Gobiet et al., 2014)
			Snow cover: -50% duration at 2000m with +4°C Snow cover: -95% duration under 1000m with +4°C Glacier cover: -80% by 2100 with +3°C Glacier cover: almost ice free by 2100 with +5°C Small glacier are expected to disappear by 2050 Glacier volume: -30% to 70% for larger glacier by 2050 The zone of warm permafrost (mean annual rock temperature approximately -2 to 0°C) which is more susceptible to slope failures than cold permafrost, may rise in elevation a few hundred meters during the next 100 years	(“Home - Climate Adaptation,” n.d.)
		EVAPORATION	Relative humidity: -0.5% in winter / -1.4% in summer by 2050 Relative humidity: +0.5% in winter / -3.9% in summer by 2100	(Gobiet et al., 2014)
			Soil water content will decline, saturation conditions and drainage will be increasingly rare and restricted to periods in winter and springs	(Field, 2014)
	TEMPERATURE	SEA LEVEL	Projections period: 2081-2100. Reference period: 1986-2005 +0.29 to 0.55 (RCP2.6) +0.36 to 0.63 (RCP4.5) +0.37 to 0.64 (RCP6.0) +0.48 to 0.82 (RCP8.5)	(Field, 2014)
			+20 to +70cm by 2100. The major coastal areas at risk of sea flooding are the Padano-Venetian, Versilia, Fondi and Pontina plains	(“Home - Climate Adaptation,” n.d.)
			Mediterranean sea: +18 to +59cm by 2100	(IDDRI, 2009)
	PRECIPITATION	FLOODS	The most important winter flood: 5 times more frequent	(Gobiet et al., 2014)
			Projected return period of a current 100-year flood: less than 20 years Flood risk: -18% (-40% to +20%) by 2030. +100% or -75% by 2100 (not univ)	(“Home - Climate Adaptation,” n.d.)
		DROUGHTS	Projections period: 2071-2100. Reference period: 1971-2000 +4.7% (B1) / 4.7% (A2) number of drought events +89.9% (B1) / +143.1% (A2) average duration +375.2% (B1) / +467.4% (A2) average deficit volume	(Gobiet et al., 2014)
		STREAMFLOWS	-21% to -31% potential groundwater recharge by the 2050, with 1%/year CO_2 increase	(“Home - Climate Adaptation,” n.d.)

ENERGY RESOURCES	CLIMATE CHANGE	WIND	Before 2050: no significant changes After 2050: decrease in wind energy in winter and summer	(Field, 2014)
		BIOENERGY	% of total land suitable are for growing biofuel crops Oilseed rape: 65% (1990) +5-15% (2020-2050-2080) Sugarcane: 35% (1990) +5-15% (2020-2050-2080) Maize: 65% (1990) +5-15% (2020) +16-30% (2050-2080)	(Tuck et al., 2006)
	WATER	RUNOFF	Reference period: 1971-2000 -13% to -15% for 2031-2060. -16% to -23% for 2071-2100 +90% in winter runoff in the Italian central alps -45% summer runoff in the Italia central alps -16% to -23% by 2050 in the Candelaro catchment in southern Italy -25% to -41% for 2070-2099 compared to 1961-1990 for Crati river basin	("Home - Climate Adaptation," n.d.)
	TEMPERATURE	HEATING DEMAND	Reference: no climate change scenario Cold/wet scenario: -11% in 2030 / -21% in 2050 / -9% in 2010-2050 Average scenario: -10% in 2030 / -20% in 2050 / -9% in 2010-2050 Warm/dry scenario: -12% in 2030 / -23% in 2050 / -13% in 2010-2050 Emissions reduction: -14% in 2030 / -7% in 2050 / -10% in 2010-2050	(Dowling, 2013)
		COOLING DEMAND	+50% electricity consumption by 2080s	("Home - Climate Adaptation," n.d.)
			Reference: no climate change scenario Cold/wet scenario: 24% in 2030 / 54% in 2050 / 24% in 2010-2050 Average scenario: 50% in 2030 / 72% in 2050 / 43% in 2010-2050 Warm/dry scenario: 36% in 2030 / 73% in 2050 / 35% in 2010-2050 Emissions reduction: 54% in 2030 / 57% in 2050 / 46% in 2010-2050	(Dowling, 2013)
ENERGY SUPPLY	TEMPERATURE	EFFICIENCY		
		• SOLAR POWER	PV output from 2010 to 2080 is likely to increase by a few percent CSP is likely to increase by more than 10%	("Home - Climate Adaptation," n.d.)
		• THERMAL PLANTS	+1°C monthly ambient temperature (Nuclear power supply) -0.7% production (near 0°C) -2.3% production (near	("Home - Climate Adaptation," n.d.)
	WATER	REFRIGERATION	Projections period: 2031-2060. Reference period: 1971-2000 -6% to -19% summer average usable capacity	(Field, 2014)
	ENERGY RESOURCES	HYDROPOWER	-6% to -36% electricity production (2071-2100 compared to present level)	(Field, 2014)
		WIND	The potential for wind energy under climate change will probably not increase	("Home - Climate Adaptation," n.d.)
		BIOFUEL	+400% water consumption by 2030 (Scenario: Reference Mix) +1600% water consumption by 2030 (Scenario: Biofuels Mix)	(Rio Carrillo and Frei, 2009)
	CLIMATE CHANGE	MITIGATION	-40% domestic reduction in GHG by 2030 compared to 1990	(European Council, 2014)

Table 9.4 Adaptation measures for energy demand and energy supply systems to climate change in Spain and Italy

VULNERABLE ELEMENTS		ADAPTATION MEASURES					
		ENGINEERING MEASURES	SPAIN	ITALY	NON-ENGINEERING MEASURES	SPAIN	ITALY
DEMAND	ELECTRICITY END USE	➢ Increase generation (MWh) and capacity (MW) ➢ Improve the energy efficiency of energy supply ➢ Improve end-use efficiency for buildings, facilities and energy-intensive appliances and machinery ➢ Reduce the need of cooling, increase cooling efficiency and decrease internal heat gains ➢ Implement energy storage technologies as further option to shift electricity consumption away from peak hours	X √ √ √ √	X √ √ √ √	➢ Require minimum energy performance standards for new commercial buildings ➢ Require a wide range of electricity-using appliances with labelling and certification ➢ Require and enforce energy performance standards ➢ Develop legislation and access to finance for energy service companies ➢ Set minimum standards for industrial electrical motors ➢ Consider subsidized programs for mass replacement of incandescent lights, and replacing old inefficient refrigerators with never efficient models ➢ Adopt the ISO global energy management standard ➢ Consider the possible use of solar photovoltaic rooftop panels to reduce summer building cooling loads	√ √ √ √ √ √ √ √	√ √ √ √ √ √ √ √
SUPPLY	HYDROPOWER	➢ Design more robust dams for heavier flooding and extreme events ➢ Increase dam height to accommodate increase river flow extremes ➢ Construct or augment water storage reservoirs ➢ Restore and better manage upstream land ➢ Construct small dams in the upper basins if flow is expected to increase ➢ Adapt or expand installed capacity to accommodate increase in flow regime ➢ Modify canals or tunnels to better handle changes in water flows ➢ Modify spillway capacities and install controllable spillway gates ➢ Modify the number and type of turbines that are better suited for expected water flow rates and more resilient to performance reductions and turbine lifetime ➢ Design regional integration through transmission connections ➢ Siting plants in locations non-threatened by Glacial Lake Outburst Flood (GLOF) risks ➢ Promote the development of smaller plants to respond to GLOF risk	√ √ √ √ √ √ √ √ √ √ X X	√ √ √ √ √ √ √ √ √ √ X X	➢ Analysis to estimate likely range of projected climate variations over hydro lifetime ➢ Identify cost-effective designs (new plants) and modifications (existing plants) to deal with specific risks identified for the site ➢ Adapt and implement in plant operation to account for changes in river flow patterns ➢ Relocate based inflow on changes in flow regime ➢ Optimize reservoir management and improve energy output by adapting to changes in rainfall or river flow patterns ➢ Operational complementarities with other sources (for example natural gas) ➢ Develop improved hydrological forecasting techniques and adaptive management operating rules ➢ Develop basin-wide management strategies that take into account the full range of downstream environmental and human water uses	√ √ √ √ √ √ √ √	√ √ √ √ √ √ √ √
	WIND POWER	➢ Construct turbines that can operate at higher wind speeds and gusts ➢ Design a foundation which support the turbine where there are changes in permafrost conditions ➢ Design offshore turbines to withstand expected increases in wind-sea wave forces ➢ Use taller towers to capture the stronger winds at higher altitudes ➢ Consider the development and commercialization of vertical axis wind turbines ➢ Consider the effects of extreme low and high temperatures in turbine ➢ Implement passive and active methods to reduce icing. Passive method: design blades with reduced ice accumulation. Active method: blade heating ➢ Integrate increased amounts of wind energy into the grid	√ X √ √ √ √ X √	√ √ √ √ √ √ √ √	➢ Choose sites for new infrastructures, or relocate existing turbines in sites that take into account expected changes in wind speeds during the lifetime of the turbines, as well as sea level rise and changes in river flooding ➢ Siting procedure to take into account expected changes in wind speeds and sea –level rise during the lifetime of the turbines ➢ Ensure the presence of rapid emergency repair teams ➢ Develop insurance schemes for long-term wind power yields and damages ➢ Develop meteorology-based weather/climate forecasting	√ √ √ √ √	√ √ √ √ √

SUPPLY	SOLAR POWER	➢ Assure structures are strong enough to withstand higher winds ➢ Specify stronger mounting structure, and cabling and components that can deal with high moisture content and flooding ➢ Specify heat-resistant PV cells and module components designed to withstand short peaks of very high temperature ➢ Use designs that improve passive airflow beneath photovoltaic mounting structures ➢ Where snowfall are heavy or likely to increase, assure free space so that snow can slide off the panel ➢ Where solar energy is likely to become more diffuse, with changes in cloud cover, rough surfaced photovoltaic modules are more efficient ➢ Where clouds are likely to pass over modules more quickly, consider micro-inverters for each panel to improve stability and increase power output ➢ Consider distributed systems which can improve grid stability ➢ For any tracking solar system for CSP, the motors and their mounting must be especially robust wherever stronger winds are expected ➢ Avoid tracking systems where cyclones are expected to increase in strength (CSP) ➢ Consider forced air and liquid coolant systems where temperature increase (CSP) ➢ Where water shortages are expected consider air cooling (CSP) ➢ Use evacuated tube collectors for thermal heating because they do not suffer from ambient temperature problems ➢ Use engineer evacuated tube collectors with higher resistance to hailstorms ➢ Use evacuated tube collectors than flat plate collector when there is more diffuse than direct insolation	✓ ✓ ✓ ✓ X ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓	✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓	➢ Develop meteorology-based weather/climate forecasting ➢ Where possible, site solar photovoltaic, CSP and thermal systems where expected change in cloud cover are relatively low ➢ Choose locations with lower probability of dust, grit and snow of practical ➢ For locations where temperature increases or significant heat waves are expected, choose modules with more heat-resistant photovoltaic cells and module materials designed to withstand short peaks of very high temperature ➢ For distributed solar systems, make available mobile repair teams to ensure functioning of systems after damage from extreme events	✓ ✓ ✓ ✓ ✓	✓ ✓ ✓ ✓ ✓
	BIOMASS AND BIOFUELS	➢ Expand irrigation systems or improve the efficiency of existing irrigation to counteract drought impact if sufficient water is available from sources outside drought-hit area ➢ Use unconventional sources if there is no availability of conventional water resources ➢ Protect against floods by building dykes and improving drainage ➢ Expansion of rainwater harvesting, water storage and conservation techniques, water reuse and desalination ➢ Improve water harvesting and use ➢ Improve soil and nutrient management ➢ Increase the robustness of biomass power plants	✓ ✓ ✓ ✓ ✓ ✓ ✓	✓ ✓ ✓ ✓ ✓ ✓ ✓	➢ Use of salt-tolerant pants (halophytes) – including varieties of sugarcane, millet and corn that grow in brackish water on saline land ➢ Adjust crop management and rotation schemes ➢ Adjust planting and harvesting dates ➢ Introduce soil moisture conservation practices to improve soil fertility ➢ Relocate crops in areas with lower risk of flooding and storms ➢ Implement early warning systems for seasonal rainfall and temperature anomalies ➢ Support emergency harvesting of biomass in case of an imminent extreme event ➢ Provide crop insurance schemes ➢ Control pests and diseases because climate change appears to be altering them ➢ Improve ecosystem management ➢ Implement efficient harvesting and early transformation of agriculture produce to reduce post-harvest losses and preserve crop quantity and quality	✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓	✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓
	WAVE AND TIDAL ENERGY	➢ Devices need to be engineered to withstand extreme waves by being massive ➢ For sea wave floating systems, consider designing for 50-year freak waves ➢ For sea wave anchorage systems, design them to be oriented in the wave direction rather than across the wave front to reduce vulnerability to severe stresses ➢ Consider protection mechanism against storm ➢ Raise level of barrage basin walls for tidal systems ➢ For OTEC, construct larger pipes to increase volume of water to the surface ➢ Design deep-sea pipes to withstand greater stresses	✓ ✓ ✓ ✓ ✓ ✓ ✓	✓ ✓ ✓ ✓ ✓ ✓ ✓	➢ Consider onshore or nearshore systems to produce electricity, because they are less vulnerable to storm damage, although the power available is less than further out at sea	✓	✓

SUPPLY	THERMOELECTRIC POWER PLANTS	➢ Develop and implement higher structural standards for new or renovated buildings ➢ Build concrete-sides buildings instead of metal because they are more resistant to wind and corrosion ➢ Raise level of structures ➢ Develop flood control where floods are likely to increase. Implement embankments, dams, dykes, reservoirs, polders, ponds, relocated flood defense, barriers and higher channel capacity ➢ Construct improved coastal defenses (seawalls and bulkheads) ➢ Improve drainage and reroute water pipes ➢ Protect fuel storage including stockpiles ➢ Change the cooling system from a once-through to a closed-circuit ➢ Redesign cooling facilities: recover water from condense and heat exchangers, reduce evaporative losses, increase secondary or wastewater usage, construct dry cooling towers ➢ Increase volume of water treatment works and develop new water sources ➢ Install additional cooling towers and modify cooling water inlets at coastal locations ➢ If cooling water is unavailable with climate change, air-cooled systems could be used ➢ Use dry or hybrid cooling systems with lower water requirements ➢ Develop more efficient pumps and heat exchangers	✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓	✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓	➢ Choose better locations (less exposed places) to build new thermal plants ➢ Concentrate investment in locations where temperatures are likely to be cooler ➢ Decentralize generation ➢ Invest in more cooling capacity and in different cooling technologies ➢ Invest in more spare production capacity and more network capacity ➢ Require more stringent safety investments ➢ Develop and implement higher structural standards for new or renovated buildings ➢ Incorporate gradual sea level rise, increased storms events and associated tidal surges into design criteria ➢ Formulate long-term strategies to respond to climate-related disruption ➢ Restore/afforest/reforest land	✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓	✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓
	FOSSIL FUEL EXTRACTION, PRODUCTION AND REFINING	➢ Build or enlarge reservoirs of water to reduce flooding risk in new and existing mining developments ➢ Reassess flood-prone areas and elevating buildings or vulnerable components ➢ Build flood-proofing buildings ➢ Power plants and pumps should preferably be sited where there is an adequate supply of cooling water ➢ Consider air cooling as an alternative to water cooling ➢ Build or improve dykes, berms and spillways onshore ➢ Build or enlarge reservoirs of water to reduce water shortages ➢ Develop or reroute water source ➢ Improve the robustness of designs, particularly offshore installation that are vulnerable to storms	✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓	✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓	➢ Site future mines in areas that have a limited exposure to flooding or drought risk ➢ Adopt techniques that slow, steer and block water flows ➢ Carry out flood hazard assessments ➢ Improve models used to predict storms	✓ ✓ ✓ ✓	✓ ✓ ✓ ✓
	TRANSMISSION, DISTRIBUTION AND TRANSFER OF ENERGY	➢ Reinforce existing T&D structures and build underground distribution systems ➢ Where stronger winds are expected, strengthen distribution poles with guy wires ➢ Where lightning strikes may increase, include lightning protection ➢ Specify more effective cooling for substations and transformers ➢ Design improved flood protection measures for the infrastructure ➢ Build a resilient high-capacity transmission system ➢ Use smart transformers which control the flow of electricity to stabilize existing aging power grids ➢ Develop and use smart grids ➢ Design more flexibility into T&D networks, allowing increased rerouting during times of disruption ➢ Reduce pressure on the grid through distributed, decentralized energy generation ➢ Take care to maintain grid stability	✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓	✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓ ✓	➢ Require higher design standards for distribution poles and towers ➢ Invest resources into building a resilient, high-capacity transmission system ➢ Improve system management through investing in smart grids ➢ Forbid the construction of power lines near dikes and ban permanent trees next to existing dykes ➢ Specify Information and Communication Technology (ICT) components that are certified as resilient to higher temperatures and humidity, and design improved redundancy into ICT systems, including wireless transmission better able to handle high temperatures	✓ ✓ ✓ ✓ ✓	✓ ✓ ✓ ✓ ✓

APPENDIX I

In this appendix we report all the vulnerability indicators presented by HELIO International in its book *Climate-proofing energy systems* (Williamson et al., 2009) and Michaelowa et al. in *Use of indicators to improve communication on energy systems vulnerability, resilience and adaptation to climate change* (Michaelowa et al., 2010). The indicators shown in Table I.1 can be divided in two groups. The ones which end with a number are the main indicators, while the others which end with a letter are expansions.

Table I.1 Table of vulnerability indicators. Created by author collecting data from (Williamson et al., 2009, p. 31-32) and (Michaelowa et al., 2010, p. 12-15)

SECTOR	INDICATOR	DESCRIPTION
HYDROPOWER	VH1	Expected precipitation change over next 20-50 years (%) and/or probability of floods in each watershed
	VH2	Projected flood frequency over the next 50 years (number of floods that have a greater intensity than a flood with a 100 year recurrence cycle)
	VH2b	Describe what % of the water is used for: agriculture, power and drinking
	VH3	Projected flood frequency over the next 50 years (number of floods that have a greater intensity than a flood with a 100 year recurrence cycle)
WIND POWER	VW1	Number of wind turbines at less than 1 m above sea level
	VW2	Projected change of average wind speed over the next 20 years, based on regional climate models (%)
	VW3	Projected share of average annual wind speeds over 25 m/s over the next 20 years (at this wind speed most wind turbines have to be switched off)
	VW4	Projected likelihood of a storm with gusts over 70 m/s reaching areas where wind turbines are located (% over 20 years). At this wind speed destruction of wind turbines is likely
SOLAR POWER	VS1	Capacity of solar installations already in place (m^2)
	VS1b	Distinguish between PV (MW) and thermal (m^2)
	VS1c	Describe sites (quality of the insulation and of the building on which systems are installed) and type of ownership (private, government, public/private partnership, etc.)
	VS2	Expected temperature (°C) increase in the next 20 years relevant for PV capacity
	VS3	Projected change in cloud cover over the next 20 years (%)
	VS4	Projected likelihood of storm gusts over 70 m/s reaching areas where solar power plants are located (% over 20 years). At this wind speed destruction of plants is likely

BIOMASS AND BIOFUEL	VB1	Proportion of biomass used for energy purposes (%) in total biomass production
	VB1b	If possible, distinguish between different sources and different applications – agricultural biomass harvest, electricity, heat
	VB1c	Forest (as defined by FAO) biomass harvest, electricity, heat
	VB2	Expected precipitation change over next 20-50 years (%)
	VB3	Probability of temperature increase beyond biological heat tolerance of relevant crop over the next 20 years (%). 20 years is the estimated average lifetime of biomass power plants.
	VB4	Projected drought frequency over the next 20 years (number of droughts that would result in a reduction of crop yields by more than 20%)
	VB5	Projected flood frequency over the next 20 years (number of floods that would result in a reduction of crop yields by more than 20%)
	VB6	Number of biomass power plants located at less than 1 m above sea level and situated in an area that has a 100 year flood cycle
	VB7	Share of sheltered storage
THERMAL POWER PLANTS	VP1	Number of thermal (coal, oil and gas) power plants located at less than 1 m above sea level and within the area that would be flooded by a flood with a current recurrence period of 100 years
	VP2	Number of nuclear power plants located at less than 1 m above sea or river level and within the area that would be flooded by a flood with a current recurrence period of 100 years
	VP3	Number of incidents/accidents since the plant was built
	VP3b	Describe the most significant incidents
	VP4	Expected temperature increase of cooling water for thermal (including nuclear) power plants over the next 30 years (°C)
	VP5	Expected number of droughts that would lead to a decrease in capacity of thermal power plants by more than 10% over the next 30 years. Thirty years is the typical lifetime of fossil fueled power plants
	VP6	Number of thermal power plants located by a river fed by glacial melt where the glaciers are unlikely to vanish over the next 30 years
FUEL FROM MINED RESOURCE	VF1	Share of offshore oil and gas installations likely to be hit by a storm of more than 70 m/s gusts over the next 20 years (%). The lifetime of such installations is not well known, but should be shorter than that of power plants. At a wind speed of 70 m/s destruction of plants is likely
	VF2	Share/number of refineries likely to be hit by a storm of more than 70 m/s gusts within the next 20 years (%)
	VF3	Number of coal mines plants located at less than 1 m above sea level and situated in an area than has a 100 year flood cycle
	VF4	Number of days of available stored stock
	VF5	Share of protected storage in tanks or covered depots
TRANSMISSION AND TRANSFER	VT1	Length of in-country, above-ground transmission and distribution lines (km)
	VT1b	Distinguish between: high (transmission); middle + low voltage lines (distribution)
	VT1c	Describe any transnational lines
	VT2	Number and length of power cuts (differentiate between failures due to weather or equipment failure and those cuts due to rationing)
	VT2b	Average hours of interruption per year
	VT3	Percentage of energy supply requiring regional transport over 50 km
	VT3b	% that is transportation of fossil fuel
	VT3c	% that is transportation of biomass

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LIST OF TABLES

LIST OF FIGURES