**UNIVERSIDAD COMPLUTENSE DE MADRID**
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# Climate change impacts on renewable energy generation and electricity demand

# Impactos del cambio climático en la generación de energía renovable y en la demanda de electricidad

MEMORIA PARA OPTAR AL GRADO DE DOCTOR

PRESENTADA POR

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# Climate Change Impacts on Renewable Energy Generation and Electricity Demand

## *Impactos del cambio climático en la generación de energía renovable y en la demanda de electricidad*

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*Principle and beginning ... of beings is the limitless ... where beings have their beginning, therein also have their end according to necessity; for they pay penalty and retribution to each other for their injustice in accordance with the arrangement of time.*

Anaximander of Miletus

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# Index

**MOTIVATION AND STRUCTURE OF THE THESIS .................. 1**

1. MOTIVATION .................. 1
2. OBJECTIVES OF THE THESIS .................. 1
3. STRUCTURE OF THE THESIS .................. 1
REFERENCES .................. 3

**CLIMATE CHANGE IMPACTS ON RENEWABLE ENERGY GENERATION. A REVIEW OF QUANTITATIVE PROJECTIONS .................. 4**

1. INTRODUCTION .................. 4
2. METHODOLOGY .................. 4
3. HYDROELECTRIC POWER PLANTS .................. 5
    *3.1. Overview, impacts and methodological issues .................. 5*
    *3.2. Main projections in literature .................. 6*
4. WIND GENERATION .................. 13
    *4.1. Overview, impacts and methodological issues .................. 13*
    *4.2. Main projections in literature .................. 15*
5. SOLAR GENERATION .................. 21
    *5.1. Main impacts and methodological issues .................. 21*
    *5.2. Main projections in literature .................. 22*
6. OTHER RENEWABLE SOURCES .................. 27
7. DISCUSSION .................. 28
REFERENCES .................. 30
APPENDIX. CLIMATE CHANGE IMPACTS ON BIOMASS GENERATION AND MOST RELEVANT STUDIES ON OTHER SOURCES OF GENERATION .................. 41

**THE IMPACT OF CLIMATE CHANGE ON THE GENERATION OF HYDROELECTRIC POWER—A CASE STUDY IN SOUTHERN SPAIN .................. 44**

1. INTRODUCTION .................. 44
2. METHODOLOGY .................. 45
    *2.1. Description of the Plants .................. 45*
    *2.2. The Physical Model .................. 46*
    *2.3. Historical Reconstruction .................. 49*
3. PRODUCTION PROJECTIONS .................. 50
    *3.1. Hypothesis for the Projections .................. 50*
    *3.2. Results .................. 51*
    *3.3. Historical Background .................. 53*
    *3.4. Alternative Sources of Information .................. 55*
4. ECONOMIC ANALYSIS .................. 56
    *4.1. Hypothesis .................. 56*
    *4.2. Analysis of Operating Margin .................. 58*
    *4.3. Investment Analysis .................. 58*

5. DISCUSSION ........ 59
6. CONCLUSIONS ........ 59
REFERENCES ........ 61

**IMPACTS OF CLIMATE CHANGE ON WIND ENERGY POWER – FOUR WIND FARMS IN SPAIN ........ 63**

1. INTRODUCTION ........ 63
2. METHODOLOGY ........ 64
  *2.1. Description of the plants ........ 64*
  *2.2. Methodological outline for the projections ........ 65*
  *2.3. Methodological outline for the economic analysis ........ 69*
3. PROJECTION ........ 71
  *3.1. Results ........ 71*
  *3.2. Context in literature ........ 72*
4. ECONOMIC ANALYSIS ........ 74
  *4.1. Analysis of operating margins ........ 74*
  *4.2. Investment analysis ........ 76*
5. DISCUSSION ........ 76
6. CONCLUSIONS ........ 77
REFERENCES ........ 78

**THE INFLUENCE OF CLIMATE ON ELECTRICITY DEMAND IN THE BASQUE COUNTRY IN THE CONTEXT OF CLIMATE CHANGE ........ 82**

1. INTRODUCTION ........ 82
2. METHODOLOGY ........ 83
3. ELECTRICITY DEMAND IN THE BASQUE COUNTRY ........ 84
4. CLIMATE EVOLUTION ........ 86
5. CORRELATION BETWEEN TEMPERATURE AND ENERGY CONSUMPTION ........ 87
6. FUTURE CLIMATE PROJECTIONS ........ 88
7. DISCUSSION ........ 90
REFERENCES ........ 92
SUPPLEMENTARY MATERIAL. CORRELATION ANALYSIS AND TEST OF STATISTICAL SIGNIFICANCE. ........ 95

**CONCLUSIONS AND FURTHER RESEARCH ........ 98**

1. OVERVIEW ........ 98
2. IMPACTS ON SUPPLY ........ 98
3. IMPACTS ON DEMAND ........ 99
4. LIMITATIONS AND FUTURE RESEARCH ........ 100
REFERENCES ........ 101

**RESUMEN ........ 102**

**ABSTRACT ........ 102**

# Index of figures

**CHANGE IMPACTS ON RENEWABLE ENERGY GENERATION. A REVIEW OF QUANTITATIVE PROJECTIONS**

FIGURE 1. TECHNOLOGICAL SCOPE OF ANALYSED PAPERS. .......... 28
FIGURE 2. GEOGRAPHICAL SCOPE OF ANALYSED PAPERS. .......... 28

**THE IMPACT OF CLIMATE CHANGE ON THE GENERATION OF HYDROELECTRIC POWER—A CASE STUDY IN SOUTHERN SPAIN**

FIGURE 1. LOCATION OF THE THREE PLANTS ALONG THE GUADALQUIVIR BASIN. .......... 46
FIGURE 2. OPERATION OF HYDROCLIM PHYSICAL MODEL. .......... 47
FIGURE 3. HISTORICAL PRODUCTION AND RECONSTRUCTION AT THE MENGÍBAR PLANT. .......... 49
FIGURE 4. HISTORICAL PRODUCTION AND RECONSTRUCTION AT THE CALA PLANT.. .......... 49
FIGURE 5. HISTORICAL PRODUCTION AND RECONSTRUCTION AT THE TRANCO DE BEAS PLANT.. .......... 50
FIGURE 6. PROJECTED PRODUCTION FOR CALA IN MWH (A2). .......... 51
FIGURE 7. PROJECTED PRODUCTION AT MENGIBAR IN MWH (A2). .......... 51
FIGURE 8. PROJECTED PRODUCTION FOR TRANCO IN MWH (A2). .......... 52
FIGURE 9. COMPARISON OF PROJECTIONS AND CLIMATE TRENDS. .......... 52
FIGURE 10. HISTORICAL EVOLUTION OF FLOW AT THE CALA CENTER. .......... 53
FIGURE 11. HISTORICAL AND PROJECTED FLOW ($M^3/S$), CALA CENTER. S. .......... 54
FIGURE 12. HISTORICAL AND PROJECTED FLOW ($M^3/S$), MENGIBAR CENTER.. .......... 54
FIGURE 13. HISTORICAL AND PROJECTED FLOW ($M^3/S$), TRANCO CENTER.. .......... 54
FIGURE 14. FLOW AND RAINFALL DATA (1967–2012), TRANCO DE BEAS CENTER.. .......... 55

**IMPACTS OF CLIMATE CHANGE ON WIND ENERGY POWER – FOUR WIND FARMS IN SPAIN**

FIGURE 1. LOCATION OF THE WIND FARMS. .......... 65
FIGURE 2. SEASONAL PRODUCTION (IN %) BY WIND FARM. .......... 72
FIGURE 3. REANALYSIS AND PROJECTIONS. .......... 74

**THE INFLUENCE OF CLIMATE ON ELECTRICITY DEMAND IN THE BASQUE COUNTRY IN THE CONTEXT OF CLIMATE CHANGE**

FIGURE 1. ELECTRICITY DEMAND IN THE THREE PROVINCES FROM 2000 TO 2017. .......... 85
FIGURE 2. QUANTITY OF HDD AND CDD PER CITY OVER TIME.. .......... 87
FIGURE 3. THE AVERAGE PROJECTED EVOLUTION OF HDD AND CDD PER PROVINCE COMPARED WITH THE REFERENCE PERIOD (2012-2017).. .......... 89
FIGURE 4. HISTORICAL AND PROJECTED (RCP 8.5) RATIO OF CDD/HDD IN FOUR AUTONOMOUS REGIONS.. .......... 90

# Index of tables

**CLIMATE CHANGE IMPACTS ON RENEWABLE ENERGY GENERATION. A REVIEW OF QUANTITATIVE PROJECTIONS**

TABLE 1. MAIN THREATS AND IMPACTS ON HYDROPOWER GENERATION. ........ 6
TABLE 2. MOST RELEVANT STUDIES ON CLIMATE CHANGE IMPACTS ON HYDROPOWER GENERATION. ........ 9
TABLE 3. MAIN THREATS AND IMPACTS ON WIND GENERATION. ........ 13
TABLE 4. MOST RELEVANT STUDIES ON CLIMATE CHANGE IMPACTS ON WIND ENERGY GENERATION. ........ 17
TABLE 5. MAIN THREATS AND IMPACTS ON SOLAR PV. ........ 21
TABLE 6. MOST RELEVANT STUDIES ON CLIMATE CHANGE IMPACTS ON PV GENERATION. ........ 24
TABLE 7. MAIN THREATS AND IMPACTS ON BIOMASS GENERATION. ........ 41
TABLE 8. MOST RELEVANT STUDIES ON CLIMATE CHANGE IMPACTS ON OTHER RENEWABLE SOURCES OF GENERATION ........ 42

**THE IMPACT OF CLIMATE CHANGE ON THE GENERATION OF HYDROELECTRIC POWER—A CASE STUDY IN SOUTHERN SPAIN**

TABLE 1. CHARACTERISTICS OF THE ANALYZED PLANTS ........ 45
TABLE 2. VARIATION OF AVAILABLE RESOURCE (RUNOFF) BASED ON CEDEX AVERAGE PROJECTIONS FOR THE GUADALQUIVIR, COMPARED WITH 1961–1990. SCENARIOS A2 AND B2.. ........ 50
TABLE 3. HISTORICAL AND PROJECTED PRODUCTION TO POWER RATIO (AVERAGE ANNUAL PRODUCTION (MWH)/CAPACITY (INSTALLED MW)).. ........ 53
TABLE 4. PROJECTED REDUCTIONS IN PRODUCTION (%). CEDEX VS. REGIONAL GOVERNMENT OF ANDALUSIA. ........ 55
TABLE 5. CAPITAL COSTS AT HYDROPOWER PLANTS. ........ 56
TABLE 6. ALIGNMENT RATIO FOR HYDROELECTRIC POWER STATIONS. ........ 57
TABLE 7. EVOLUTION OF OPERATING MARGINS AT PILOT CENTERS. ........ 58
TABLE 8. EVOLUTION OF OPERATING MARGINS (%) OVER TIME. ........ 58
TABLE 9. NET PRESENT VALUES OF INVESTMENTS IN PILOT CENTERS, A2 AND B2 SCENARIOS. ........ 59

**IMPACTS OF CLIMATE CHANGE ON WIND ENERGY POWER – FOUR WIND FARMS IN SPAIN**

TABLE 1. CHARACTERISTICS OF THE ANALYZED PLANTS ........ 64
TABLE 2. RESULTS FOR THE ADJUSTED PRICE (AP), SEASONAL DEVIATION (SD) AND ALIGNMENT RATIO (AR). ........ 70
TABLE 3. CAPEX AND OPEX VALUES FROM LITERATURE (CLOSEST VALUES TO SPAIN HAVE BEEN INCLUDED WHEN AVAILABLE). .. 70
TABLE 4. HISTORICAL AVERAGE WIND SPEED VERSUS MEDIUM AND LONG-TERM PROJECTIONS.. ........ 71
TABLE 5. HISTORICAL AVERAGE PRODUCTION VERSUS MEDIUM AND LONG-TERM PROJECTIONS.. ........ 72
TABLE 6. FULL LOAD HOURS AT EACH WIND FARM. ........ 74
TABLE 7. OPERATING MARGINS AT EACH PLANT IN THE REFERENCE PERIOD AND IN THE PROJECTIONS UNDER OFFICIAL COST PARAMETERS ........ 75
TABLE 8. OPERATING MARGINS AT EACH PLANT IN THE REFERENCE PERIOD AND IN THE PROJECTIONS UNDER COST PARAMETERS PROVIDED BY ACCIONA. ........ 75
TABLE 9. OPERATING MARGINS AT EACH PLANT IN THE REFERENCE PERIOD AND IN THE PROJECTIONS UNDER OFFICIAL COST PARAMETERS ........ 75
TABLE 10. NET PRESENT VALUES OF INVESTMENTS IN THE WIND FARMS. RCP 4.5 AND 8.5.. ........ 76

**THE INFLUENCE OF CLIMATE ON ELECTRICITY DEMAND IN THE BASQUE COUNTRY IN THE CONTEXT OF CLIMATE CHANGE**

TABLE 1. SECTOR DISTRIBUTION OF ELECTRICITY DEMAND FROM 2012-2017.. ................................................................ 85
TABLE 2. CORRELATION BETWEEN DEMAND AND HDD+ CDD BY PROVINCE AND SECTOR. .................................................. 87
TABLE 3. ANALYSIS OF SENSITIVITY OF CORRELATIONS IN THE RESIDENTIAL SECTOR TO HDD AND CDD THRESHOLDS. ................ 88
TABLE 4. THE PROJECTED DECREASE IN CONSUMPTION, ECONOMIC SAVINGS, AND EMISSIONS REDUCTIONS IN THE RESIDENTIAL SECTOR FOR THE THREE PROVINCES COMPARED TO THE REFERENCE PERIOD (2012-2017).. ........................................ 89

# Acronyms and abbreviations

- AR5: Fifth Assessment Report of the IPCC.
- AEMET: State Meteorology Agency of Spain.
- CDD: Cooling Degree Days.
- CAPEX: capital expenditure.
- CEDEX: Center for Studies and Experimentation of Public Works (CEDEX) under the Ministry of Public Works in Spain.
- CFSR: Climate Forecast System Reanalysis by the National Centers for Environmental Prediction.
- CIRA: Climate Change Impacts and Risk Analysis Project from the US Environmental Protection Agency.
- CSP: Concentrated Solar Power.
- ENSO: El Niño–Southern Oscillation.
- EURO-CORDEX: Regional climate model inter-comparison project.
- EVE: Basque Energy Agency (Basque Government).
- GCM: Global Circulation Model.
- GDP: Gross Domestic Product.
- GHG: Greenhouse Gas.
- GW: Gigawatt.
- HDD: Heating Degree Days.
- IDAE: Institute for the Diversification and Saving of Energy under the Ministry for the Ecological Transition in Spain.
- IEA: International Energy Agency.
- INE: Spanish Statistical Office.
- IPCC: Intergovernmental Panel on Climate Change.
- IRENA: International Renewable Energy Agency.
- IS: Investment subsidy.
- kWh: Kilowatt hour.
- LCOE: Levelised Cost of Energy.
- MERRA 2: Modern-Era Retrospective analysis for Research and Applications, Version 2, by NASA.
- MW: Megawatt.
- MWh: Megawatt hour.
- NCEP: Climate Forecast System Reanalysis, by the National Center for Environmental Prediction (NCEP) in the US.
- OECD: Organisation for Economic Co-operation and Development.
- OMIE: Operador del Mercado Ibérico (Iberian Market Operator).
- OPEX: operational expenditure.
- PV: Photovoltaic.
- RCM: Regional Circulation Model.
- RCP: Representative Concentration Pathway of the IPCC.
- SAIH: Automatic Hydrologic Data Collection System, of the Ministry for the Ecological Transition in Spain (former Ministry of Agriculture, Food and Environmental Affairs).
- SRES: Special Report on Emissions Scenarios by the IPCC.
- UK: United Kingdom.
- UKCP: UK Climate Projections.
- US, USA: United States of America
- USD: US Dollar.

# Motivation and structure of the Thesis

## 1. Motivation

Climate change has become an increasingly important area of research and as a result an exponential increase of scholarly publications on this topic has been registered in the last few years [1,2]. Within climate related areas, risks and adaptation played a smaller role in literature and in the reports by the Intergovernmental Panel on Climate Change (IPCC) until its Fourth Assessment Report [1,3]. This gap is still relevant in practical issues like climate finance [4].

Climate change is not a yes or no issue. We are already dealing with changes caused by climate change, and irrelevant to the scenario and how quickly or in what capacity the international community reacts to reduce the causes of anthropogenic climate change, humans will have to face these impacts [5].

The paradox of electricity generation is that it is the economic sector with the highest Greenhouse Gas (GHG) emissions due to the use of fossil fuels [6]. But at the same time, it will be severely affected by the impacts of climate change [7,8]. This will impact electricity supply and also demand, as it can alter consumption patterns in various sectors [9].

Renewable energies are usually mentioned as one of the most promising solutions the sector can offer reduce of GHGs [10,11]. But they rely on resources that depend on climate variables and therefore can also be affected by climate change [12].

## 2. Objectives of the Thesis

This thesis addresses climate change impacts on renewable energies and demand, building upon existing literature and trying to provide specific examples so that the impacts can be understood and valued. To do so, the papers included here provide economic estimates of the identified changes, which is one gap that has been found in most existing research on this topic.

The objective, therefore, is to analyse and quantify the specific effect on the generation and demand of electricity in real scenarios. In this sense, we focus on certain plants or limited geographical areas in order to provide useful methods and approaces for decision makers.

To this end, the thesis combines a first opening chapter, which summarizes the state of the art in terms of impacts on renewable energy, with three quantitative chapters. Each of the latter is dedicated to unravelling the specific impact of climate change on hydroelectric and wind generation, as well as on demand. To do so, we use different numerical methods that allow for the inclusion of climate projections in models that explain the operation of each system.

Quantifying these specific impacts is not simple, due to the large number of variables that can affect the energy sector in the long term. The approach used is based on applying the expected changes to each *ceteris paribus* reference scenario. This does not prevent the analysis of other physical, economic, or regulatory variables that may be relevant in each case and vary the expected scenario.

In the same regard, due the large number of issues that could influence the areas analysed in the long term, each chapter focuses on the most relevant climatic variable for the field of study (runoff, wind speed, and temperature), which will be adapted to the needs of the models used and interrelated with the context of each chapter.

In all chapters we have worked together with parties directly related to the object of the study, such as managers of the hydroelectric and wind plants, public administrations, and autonomous bodies in charge of energy. The responsibility, in any case, is solely and exclusively of the authors.

## 3. Structure of the Thesis

The thesis as a whole is made up of four chapters. All of them have been published or accepted for publication as papers in various scientific journals. A reference will be made at the beginning of each chapter.

The first chapter was originally intended as an introduction to the thesis, but soon became a piece of research in and of itself. It provides an overview of existing studies that offer quantitative projections of climate change impacts on renewable generation. It addresses hydropower, wind generation, solar and other renewable sources and summarizes the impacts and the most relevant studies on each topic.

To do so, this chapter analyses more than 150 references on the matter in an attempt to offer a guide for researchers and decision makers on the existing projections for each field and technology, while also showing the methodological divergences and uncertainties that they address. The results should be interpreted with caution for these reasons and, furthermore, because most references are very recent, as explained in the text. In any case, important consequences for the sector can be drawn from the observations of the trends shown. Those working in the field called for such a review, which also provides a broad context as an introduction to the remaining chapters.

The second and third chapters focus on hydropower and wind generation, respectively. Both papers use some modelling to project production under climate change scenarios and provide economic estimates of the changes as well as conclusions for the design of policies in this area. They are, as far as we know, the only existing works that combine a specific and concrete analysis for generation plants with an economic study of operating margins and investment parameters.

The second chapter analyses three hydroelectric power plants in Southern Spain combining climatological, technical and economic data and projections. A physical model is applied to reproduce the plants' operations and project future flow and production under climate scenarios. The operation of these plants is simulated using an engineering model, which quantifies how the production of different types of plants changes based on variables such as plant's net height, expected daly flow rate, or efficiency factors. The model has been adjusted to the different types of plants studied: run-of-river (Mengíbar), annual reservoir (Cala), and multiannual (Tranco de Beas).

An analysis of operating margins and investment parameters is conducted showing that climate change may pose a significant threat to the operation of the plans and to future investments. In the context analysed in the first chapter, these implications are highly relevant for much of Southern Europe. The analysed loss of hydroelectric production would not only have implications for direct costs, but also for supply security and the mitigation of climate change.

The third chapter is dedicated to wind power generation and studies four wind farms in Spain. Several methods were tested and the projection was eventually based on ex post power curves, obtained by analyzing the historical performance of each farm. This means calculating the average active power per bin of wind speed throughout the historical period.

A projection of wind speed is later carried out by conducting a downscaling of an ensemble of climate models for two scenarios. Results show how these scenarios may affect production, operating margins and investment parameters. The seasonality of production is also expected to change. In the study, climate change impacts are compared with current and ongoing changes in the sector's regulatory framework.

The fourth paper analyses climate change impacts in electricity demand in the Basque Country (Spain). The methodology is based on the analysis of the thermal distance on cold and warm days with respect to established thresholds (*Heating Degree Days and Cooling Degree Days*). This distance was found to be better correlated with demand in the residential sector than in others. Based on climate projections, the future demand is projected. The implications in terms of demand, economic savings and emissions are discussed.

The main conclusions of the article are that it appears likely, in the context of the assumptions presented, that climate change will imply net economic savings, as well as a reduction in both consumption and emissions. The fundamental reason being that, although the increase in temperature is expected to be greater in summer than in winter, in a climate like that of the Basque Country the deviations from comfort temperatures are more significant in the winter. In any case, research must continue in order to confirm these results, given that there is an open debate on this in the literature.

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# Climate Change Impacts on Renewable Energy Generation. A review of quantitative projections[1]

Abstract: Research on climate change impacts on renewable energy is becoming increasingly relevant due to the vulnerability of the sector and to the continual development of methodologies and availability of data. Public and private decision-making needs specific research. However, many gaps still exist in certain geographical regions and technologies. This paper addresses the most relevant studies that project quantitative estimates of climate change impacts on solar, wind, hydro and other renewable generation technologies. Summary tables of impacts and projections are provided so that researchers, governments and the private sector may have an accurate view of the state-of-the-art on this topic.

Keywords: climate change, climate change adaptation, renewable energy, energy economics.

## 1. Introduction

Renewables will be key in a low carbon future. In order to meet the 2ºC climate goal, the share of renewable energy in the final energy consumption must increase from 19% in 2017 to 65% by 2050 [1]. By then, the share of renewable energy in electricity generation should be roughly 85%, up from an estimated 25% in 2017.

The physical impacts of climate change are among the challenges that renewables will have to face, as they have implications for the reliability and performance of the energy system [2,3]. Initial studies on this topic addressed the vulnerability of the energy sector from a demand perspective, but there are a growing number of studies analysing impacts on supply as well [3]. Transmission lines and other areas along the value chain of the energy sector can also be affected [4,5].

One of the reasons why the energy sector has received so much attention in the literature is because of the long lifespan of energy infrastructure [6]. Within the energy sector, renewable generation is the focus of most studies, due to the fact that its main resource is directly linked to climate variables such as precipitation, temperature, irradiation or wind [7]. Water is a key variable, as its availability not only affects hydroelectric power plants, but also any generation plant that depends on water for part of its process, including thermal generation [8] or even carbon capture and storage [9].

The goal of this paper is to conduct a review of studies that provide a quantitative estimate of climate change impacts on renewable energy. Notwithstanding methodological differences and regional variations, the authors consider this useful not only to researchers and the public sector, but also to sectoral experts working to incorporate climate impacts into energy sector decision-making processes around the world. The following section gives a description of the scope and methodology of this paper. Sections 3-6 provide a summary of studies regarding solar, wind, hydro and other renewable generation technologies. The paper closes with some discussion and concluding remarks.

## 2. Methodology

Most of the existing literature on this topic can be divided into the following categories.

- Most references provide an overview of potential climate change impacts on energy, with some specific section for renewable energy. These studies focus on identifying and analysing risks more than on their specific quantification [10].

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[1] This chapter has been accepted for publication as a paper in the journal Renewable & Sustainable Energy Reviews (RSER) (September 22, 2019).

- Many references focus on one technology and provide projections of potential changes in the resource or generation. The scope of these papers can be global, continental, national or even locally focused on specific power plants.
- Another group focuses on a geographical area (mostly countries, but also continents, regions or cities), projecting how various technologies can evolve under climate change scenarios and affect the energy market.
- Only a few references, usually global assessments or studies related to hydropower, provide economic estimates for the expected changes.

This review has been organized by technology rather than geographical area, so that the specific complexities of each technology can be better understood. Due to the vast amount of existing literature for some technologies (particularly covering hydro and wind), the authors have focused on studies with at least a national scope, or those that provide valuable insights or innovations. At the same time, in these cases, more recent and specific papers have been prioritized.

Common limitations and uncertainties of these studies will be analysed later. In any case, the reader must to be cautious when comparing results, as often there are differences in models, scenarios, projection methods and timeframes. Summary tables have been included at the end of each section in order to provide a clearer overview, and to make it easier to check specific references. Only papers with quantitative models and estimates have been included in the tables.

When it comes to the scenarios, studies conducted before 2014 tend to use scenarios by the SRES [11] while later studies are usually based on those by the AR5 [12].The former is based on four families of emission scenarios (A1, A2, B1 and B2) depending on the focus of future development (economic -A- or environmental – B-) and on its homogeneity (globalized -1- or with a regional focus -2-). The latter provides four trajectories of greenhouse house concentrations in the long term (2.6, 4.5, 6.0, and 8.5 W/m2). The higher the concentration, the higher the projected increase of global temperature. The pathways were built with Integrated Assessment Models (IAMs) under several assumptions related to energy, demography or the economy.

## 3. Hydroelectric power plants

### 3.1. Overview, impacts and methodological issues

Hydroelectric generation provides more than 1000 GW of installed capacity, but annual increases are waning. China, Brazil, Canada and the US are global leaders in annual installed capacity [13]. The share of hydro in total generation is expected to decrease by 2050, due to the spike in energy demand and in other renewable technologies [1]. According to the same source, total installed capacity should increase from 1248 GW in 2015 to 1828 GW in 2050. Areas with the greatest gross potential are Asia, America and Central Africa [14].

The levelised cost of hydroelectric generation has increased from 0.04 USD/kWh in 2010 to 0.05 in 2017 [15]. Hydroelectric generation is characterized by high capital costs, which can make it vulnerable to long-term impacts, as the investment horizon is typically several decades [16,17].

Assessing climate change impacts on hydropower is complex, due to nonlinear and region-specific changes in precipitation and temperatures [3]. In any case, the literature on hydropower is vaster than that on other technologies. Most studies focus on variations in streamflow due to changes in precipitation and temperature.

Run-of-river plants, which lack water storage, are significantly affected by daily and seasonal changes [4,6]. Storage capacity can be valuable when matching the inflow of water with the operational capacity of the plant [6,18]. However, the additional capital costs for storage plants may not be economically justified, due to changes in the resource in some cases [18–20].

Overall impacts on hydropower are projected to be smaller when compared to other technologies, but local impacts will most likely be greater. Therefore, from an economic standpoint there is a clear risk to financial returns on investments as certain studies have shown [19,21]. This is why the literature on hydropower includes economic assessments more often than that on other technologies.

The main climate threats and impacts on hydropower are shown in Table 1.

**Table 1.** Main threats and impacts on hydropower generation.

| CLIMATE THREATS | IMPACTS |
|---|---|
| 1. *Change in rainfall patterns* | a) Changing annual or seasonal patterns can impact river flows and water levels affecting production [3,4,22]. Not only a reduction in flow can be negative; an increase can also affect operational conditions depending on the capacity of the plant [21].<br>b) Changes in precipitation and temperature may affect the moisture levels of soil, which provides storage and regulates runoff [21].<br>c) Siltation as a consequence of erosion can affect the soil and reduce power output [4,21]. |
| 2. *Flooding and intense rain* | a) Flooding can damage infrastructure and increase the need for spilling water [4,19].<br>b) Flooding may pose a significant risk to dam safety [17,23].<br>c) Flooding can also transport debris and damage dams and turbines [3]. |
| 3. *Air temperature* | a) Higher air temperature would increase surface evaporation, reducing water storage and power output [4,20].<br>b) Ice melting can alter the seasonal inflow of water to plants that rely on snowfalls or glaciers [6,21] and pose safety risks [23]. However, it might lead to early gains for some plants [24].<br>c) An increase in temperature might increase operational costs and affect the efficiency of the equipment [24]. In particular, it can affect gate performance and cause mechanical stress [23]. |
| 4. *Others* | a) El Niño Southern Oscillation influences precipitation and has been found to affect production in some areas of America, the Iberian Peninsula, Asia and the Pacific [25]. Southern Africa could be impacted as well [20].<br>b) The performance of gates can be affected by an increase in sediment content in the water and suspended materials [23].<br>c) Landslides increase the level of sediments in water, which can cause other problems, especially in areas with high agricultural activity [22].<br>d) Increased intensity and frequency of storms and extreme weather events may affect the plants [21].<br>e) Conflicts with other uses (especially irrigation) can affect the availability of water [19,20]. |

### *3.2. Main projections in literature*

Globally, the results of existing studies differ due to differences in methodology and the Global Circulation Model (GCMs) considered [26]), but also because some studies focus on projected production whereas others center on hydropower potential [27]. If the increase in potential is located in areas with little installed capacity, production may in fact decrease [28].

In terms of production, the trend projected by Reference [18] is of a very slight increase (<1%) but with stark regional differences. A later study [27] projects a global increase in gross potential of between 2% and 6%, while a more recent paper [26] provides a less clear projection of production (from -8% to +5% depending on the scenario). Combining economic and physical information, Reference [29] projects a global change in generation of between 0.9% and 2.4%.

Two of these papers provide an economic evaluation of the changes. One of them [26] projects a very small change in expected investments (0.5%), and the other [29] uses a general equilibrium model to assess expected changes in GDP, which are modest (+/- 0.2%).

Global papers provide different geographical projections. For the US, for example, some papers [18,29] project an increase in generation and others a decrease. Regarding Europe as a whole, all studies project a decrease. The trend for other continents is less clear, but usually Asia and Central/East Africa show the biggest increases.

Specific studies on Europe confirm the above-mentioned projections, estimating an increase in generation/potential in the north and certain Central European locations, and a stark decrease in the south with maximum changes of +/- 20-25% [30–32]. A few models project decreases in hydropower potential of close to 30% in Greece, Spain and Portugal, which are the most affected countries [30]. This is consistent with some evidence of a reduction in global runoff throughout the 20th century [33], with clearer evidence in Southern European countries since the 1970s [31]. Some studies [8,34,35] project a decrease in generation/potential in Germany, Austria and Croatia.

Many papers focus on Alpine hydropower due to the specific impacts linked to snow-influenced environments. The results vary significantly [36,37], which shows the complexities of the quantification of expected flows in these environments.

In the Americas, the US is by far the most studied area. The complexity found in global studies is also present in more specific papers. Two reports to Congress have offered varied results depending on geography and models [38,39]. In the latest assessment, half of the models suggest a global increase in generation whereas the other half project a decrease. A recent paper [40] provides a very different picture, projecting a global increase in generation mainly driven by increases in the Northwest[2]. Seasonal variations are expected to be highly relevant and to affect the availability of hydro generation throughout the year. Targeted studies have been conducted in several areas of the country [41,42].

There are fewer studies covering the rest of the American continent. In Central America, projections point towards a decrease in precipitation and an important increase in droughts [43,44]. In Costa Rica, one study [45] projects huge decreases in hydropower production (-41-43%). When it comes to the Caribbean, no quantitative projections have been found, but run-off decreases have been predicted for this area. The most affected countries would be the Dominican Republic, Haiti, eastern Caribbean small island states, Mexico and Guatemala [7].

Regarding South America, precipitation is expected to change as well. There is a consensus on some seasonal variations, such as an increase in summer precipitation over eastern tropical South America and a reduction of winter precipitation over most of the continent [46]. Brazil has been extensively studied because of its high hydroelectrical production, and reductions have been projected for the country [47–49], as well as for Colombia [50].

A drop in precipitation is expected for all seasons in some areas of the Andean region [46]. In Ecuador, a recent study provides a wide range of estimates for changes in production (from -55% to +39%) [51]. On the other hand, a study in Chile [52] suggests a reduction in hydroelectric production of between 5% to 6% in the short term and 13% to 18% in the long term.

Asia and Africa have received less attention. Existing studies in China tend to confirm the increasing trend forecasted by global studies, although the timeframes differ and there are regional differences [53,54]. Regarding India, a recent study projects a significant increase in precipitation, flow and hydropower production (up to 25%) for large hydropower projects [55]. However, the high variability of rain and runoff projected by some models and the impacts of glacier melting may jeopardize hydroelectric projects in the region [56,57].

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[2] Which contradicts a previous paper that projected a decrease in the region [42].

With respect to Africa, Southern Africa is expected to be highly vulnerable and a relevant decrease in rainfall is predicted [58]. The river Congo appears to be less vulnerable, while the Zambezi River is expected to face higher impacts [21]. In the case of the latter, one study projects impacts from changes in streamflow, but also dry years, flooding and increasing water demand [59]. A more recent paper concluded that many projects in this basin face significant climate change risks [20].

Table 2 provides further details on the most relevant studies on this topic.

**Table 2.** Most relevant studies on climate change impacts on hydropower generation[3].

| **GLOBAL OR REGIONAL** | | | | | | |
|---|---|---|---|---|---|---|
| **Reference** | **Geographic area** | **Generation source** | **Scenarios** | **Reference period** | **Projection period** | **Projected changes** |
| [29] | *World* | Hydro | AR5 RCP 2.6 and 8.5 | 1960-1989 | 2010-2099 | Changes in generation are globally small (0.9-2.4%). The biggest declines are projected in the Middle East, Turkey and Brazil, whereas large increases are predicted for India, Canada and the former Soviet Union. Predicted changes in GDP are consistent with this, but more modest. |
| [26] | *World* | Hydro | AR5 RCP 4.5 and 8.5 | Present situation | 2100 | The projection depends on the scenario (changes in generation between -8% and +5% under RCP 8.5 and between -4% and +4% under RCP 4.5). The greatest decreases are projected for Europe, Mexico and the Middle East and greatest increases for East Africa, South Asia and Canada. Global investments are not expected to change more than 0.5%. |
| [27] | *World* | Hydro | AR5 RCP 4.5 and 8.5 | 1971-2000 | 2080 | Global gross potential is projected to increase by between 2.4% (RCP 4.5) and 6.3% (RCP 8.5). Increases are projected in Central Africa, India and northern latitudes. Decreases in the US, Europe, Eastern Asia, southern parts of America, Australia and Africa. |
| [18] | *World* | Hydro | SRES A1B | 2005 | 2050 | Global changes in hydro generation are projected to be small (less than 1%) assuming no changes in current hydropower installed capacity. However, there are regional differences: in Asia and America generation is mainly projected to increase, whereas in Europe the trend is the opposite (except in the north). The trend for Africa is more difficult to ascertain. |
| **EUROPE** | | | | | | |
| **Reference** | **Geographic area** | **Generation source** | **Scenarios** | **Reference period** | **Projection period** | **Projected changes** |
| [30] | *Europe* | Hydro (and wind and thermal generation) | 1.5ºC, 2ºC and 3ºC based on AR5 RCP 4.5 and 8.5 | 1971-2000 | The earliest 30-year periods when global mean temperature exceeds 1.5, 2 and 3ªC. | Mean gross hydropower potential increases in Northern, Eastern and Western Europe and decreases in Southern Europe. Countries with reductions are Greece, Spain and Portugal. Taken together, the ensemble mean projection does not exceed 10% for 1.5 ◦C, 15% for 2 ◦C or 20% for 3 ◦C. |

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[3] Studies are shown in a way that makes it easier to compare similar papers, starting with the most recent literature. They are organized first according to their geographical area, so that studies with a wider scope are presented first. Then they are grouped by comparable geographical areas. Lastly, within a comparable area, more recent studies are shown first.

| | | | | | | |
|---|---|---|---|---|---|---|
| [32] | *Europe* | Hydro (and other) | SRES A1b and E1 | 2010 | 2100 | A reduction in global generation is projected of between 2% and 8% depending on the scenario. In some Southern, Eastern and Central European countries the reduction could be roughly 20%, whereas in Northern European countries the increase may exceed 20%. |
| [31] | *Europe* | Hydro | SRES A1B | 1961-1990 | 2020s, 2070s | A clear decreasing trend in hydropower potential is seen in Southern Europe and parts of East-Central Europe, particularly in Spain, Bulgaria, Ukraine and Turkey (with maximum decreases of more than 25%). A clear increasing trend is found is large areas of Northern Europe, particularly in Norway, Sweden, Finland and Russia (with maximum increases of more than 25%). |
| [35] | *Germany and Austria* | Hydro (among others) | SRES 4AR A1b | 1971–1989 | 2051–2080 | The mean annual hydro power electricity generation for Austria and Germany is projected to decrease by 5.5%. A clear shift from summer to spring is observable. |
| [8] | *Germany* | Hydro (among others) | AR5<br>RCP 2.6 and 8.5 | 1981–2010 | 2015-2050 | RCP 2.6 suggests an overall reduction in hydropower potential, especially in many areas of Northern Germany, but never greater than 20%. RCP 8.5 projects greater reductions. |
| [34] | *Croatia* | Hydro (along with solar and wind) | SRES A2 scenario | 1961-1990 | 2011-2040 and 2041-2070 | A reduction of more than 10% in the production of electricity from hydro power plants could be expected after 2050. |
| [37] | *South-East Alpine Region* | Hydropower | SRES A1B | 1971-2000 | 2040-2070 | An increase in precipitation and hydropower is projected in almost all sites and scenarios. Increase in potential can be as high as +193% in one specific plant. Changes in seasonality are projected as well. |
| [36] | *Swiss Alps (Dam of Mauvoisin)* | Hydropower | Ad-hoc | 1961-1990 | 2070-2099 | The median future production is expected to fall by 36%. This decrease is due to the reduced availability of water (less precipitation, ice melting and evapotranspiration). |
| **AMERICA** | | | | | | |
| **Reference** | **Geographic area** | **Generation source** | **Scenarios** | **Reference period** | **Projection period** | **Projected changes** |
| [39] | *US* | Hydropower | AR5 RCP 8.5 | 1966-2005 | 2011-2050 | There is no agreement between the models on the total change in generation (half of them project an increase and half a decrease). Regarding seasonal variations, an increase in winter and spring and a decrease in summer and autumn are projected. |
| [40] | *US* | Hydropower | From the CIRA Project (Reference scenario, Pol 4.5, Pol 3.7). | 2005 | 2025, 2050 | An increase in generation is projected driven by the important increase in the Pacific Northwest region. However, under a “firm energy criteria”, a decline in reliable generation is projected due to expected seasonal variations. |

| | | | | | | |
|---|---|---|---|---|---|---|
| [38] | *US* | Hydropower | SRES A1B | 1960-1999 | 2010-2024<br>2025-2039 | Highly variable trends in the projected precipitation and runoff. Most increasing regions are in the central North and decreasing areas in the South and Northwest. The only statistically significant changes are seasonal variations in some regions. |
| [42] | *Northwest US* | Hydropower | 3AS A1F1, A2, B1, B2 | 1961-2002 | 2020s-2080s | Most models project a decrease in generation in this area and a reduction in revenues. Using 4AR scenarios the results are slightly less severe. |
| [48] | *Brazil* | Hydropower | SRES A1B | 1960-1990 | 2011-2100 | A reduction in the hydropower energy fraction is predicted over time, which will cause a yearly loss of 5.13 billion USD for the existing generation system and 12.2 billion USD for the future generation system. |
| [47] | *Brazil* | Hydropower | AR5 RCP 4.5 and 8.5 | 2010 | 2050 | Hydropower will remain the major source of electricity generation in the country but will lose relative importance. Impacts are more intense under RCP 8.5 than under RCP 4.5. |
| [49] | *Brazil* | Hydropower (among others) | SRES A2, B2 | 2006 | 2071-2100 | A reduction in power is projected for all basins except Paraná River and Grande (for the A2 scenario). Reductions range from 1-7% in scenario B2. |
| [45] | *Costa Rica* | Hydropower | SRES A2, A1B and B1 | 2009 | 2100 | Results show a reduction in hydropower production in all scenarios, estimated between 41% and 43%. |
| [51] | *Ecuador* | Hydropower | AR5 RCP 4.5 | 1971-2000 | 2071-2100 | There is much uncertainty surrounding projections. Regarding annual average inflow, estimated changes are between -85% to +277%, and for production between -55% and +39%. |
| [52] | *Chile* | Hydropower | SRES A2, and B1 | 1970-2000 | 2010-2100 | An overall reduction in hydropower production is expected for the Interconnected Central System. The reduction is projected to increase over time: 5-6% for 2010-2040, 10-12% for 2040-2070 and 3-18% for 2070-2100. |
| [50] | *Colombia (Sinú-Caribbean Basin)* | Hydropower | SRES A2, and B2 | 1964-2005 | 2010-2039 | The production of hydropower is expected to change between 0.6% and -35.2% depending on the model (only one projects an increase). |
| **ASIA** | | | | | | |
| **Reference** | **Geographic area** | **Generation source** | **Scenarios** | **Reference period** | **Projection period** | **Projected changes** |
| [54] | *China* | Hydropower | AR5 RCP 2.6, 4.5 and 8.5 | 2011 | 2100 | Hydropower generation is expected to increase under all scenarios, potentially reaching as much as 23% by the end of the century. |
| [53] | *China* | Hydropower | AR5 RCP 2.6 and 8.5 | 1971-200 | 2010-2084 | Both scenarios show a small decrease in gross hydropower potential before the 2030s and an increase afterwards. Decreases are projected for the southeast region and increases for most of the rest. |
| [55] | *India* | Hydropower | AR5 RCP 2.6, and 8.5 | 1951-2007 | 2010-2099 | Precipitation is projected to increase around seven large hydropower projects, along with a substantial rise in mean temperature. This is related to higher precipitation during the |

| | | | | | | |
|---|---|---|---|---|---|---|
| | | | | | | monsoon season. Under RCP 8.5, this would mean increases of up to 45% in streamflow and up to 25% in hydropower production. |
| **AFRICA** | | | | | | |
| **Reference** | **Geographic area** | **Generation source** | **Scenarios** | **Reference period** | **Projection period** | **Projected changes** |
| [20] | *Southern Africa (Zambezi River)* | Hydropower | Ten ad hoc scenarios derived from SRES A2 | 1961-1990 | 2050-2070 | A reduction in generation is projected for all existing plants, except one. Higher temperatures and increase in evaporation may neutralize the increase in precipitation. Regarding future projects, the results will depend on whether irrigation is prioritized over hydropower, but many projected plants may not reach their targets. The influence of El Niño Southern Oscillation (ENSO) adds uncertainty to future projections. |
| [59] | *Southern Africa (Zambezi River)* | Hydropower | SRES A2 | 1970-2000 | 2010-2040<br>2040-2070 | A reduction in hydropower potential is expected for both existing and proposed plants. The trend would have an inverted U shape for all plants, with some increases until 2017 in the first period and until 2050 in the second. |

## 4. Wind generation

### *4.1. Overview, impacts and methodological issues*

Wind energy generation in 2017 accounted for 539 GW of installed capacity, including almost 20 GW of offshore capacity worldwide, the majority of which comes from China, the US, Germany and India [13]. In order to meet the 2ºC target, wind generation should increase from around 3.5% of global generation in 2015 to 36% in 2050. This would require an investment of more than 5 trillion USD in onshore generation [1].

As wind turbines become bigger and taller, they also become more vulnerable [60]. Safety margins in the design and operation of offshore wind turbines should be increased to adapt to climate change [61].

The levelised cost of onshore wind is among the lowest in renewable generation, with a slight reduction from 0.08 USD/kWh in 2010 to 0.06 in 2017. Offshore wind is still more expensive, at 0.14 USD/kWh in 2017 [15]. Usually wind farms face high capital expenditure and low operational costs [62].

Wind is more sensitive to model formulation than other technologies [63]. There is some debate over the capacity of climate models, especially GCMs, to fit with observed data and to simulate long-term trends [64,65], but they are still the most trusted source for projections [66]. There is also uncertainty surrounding how to separate the climate signal from the climate's inherent variability, as well as regarding long-term records of wind speeds [65].

This is why, for some authors, focusing on projected changes is considered more accurate than relying on absolute predictions [67]. It is also key to provide estimates adapted to the height of wind turbines and for the upper percentiles of the wind speed probability distribution, not just the mean speed [65].

Output is highly dependent on wind speeds, and a small change can have a substantial impact on electricity generation [4]. Therefore, a large percentage of existing studies focus on wind speed, while only a few provide estimates of changes in wind direction. The statistical significance of the trends is often hard to assess [68].

Most studies focus on Europe and North America, and on changes in mean wind speed. Therefore, further studies should be developed regarding other regions and extreme wind events [60]. While the vast majority of studies focus on onshore production, offshore turbines are more vulnerable to higher wind speeds and maintenance is usually more expensive [60]. Assessing the impacts on them is more complex due to information gaps, and because GCMs struggle to represent offshore wind near the coast [69].

Regarding extreme wind speeds, loading conditions used in the design of turbines are based on studies in Europe, and may not be representative in other regions [70].

There are only a few studies that delve into the financial implications of climate change impacts on wind, focusing on a national level [62,71] or on individual wind farms [72].

There is also some debate over the opposite question of whether a massive deployment of wind energy could alter local weather conditions. So far, no major changes are anticipated, at least in Europe [73].

The main climate threats and impacts on wind generation are shown in Table 3.

**Table 3.** Main threats and impacts on wind generation.

| CLIMATE THREATS | IMPACTS |
|---|---|
| *1. Changes in wind speed* | a) <u>Changes in wind speed can reduce generation</u> (as turbines cannot operate in very high or very low winds) [4]. |

| **CLIMATE THREATS** | **IMPACTS** |
|---|---|
| | b) Within operational wind speeds, output is greatly affected by wind speed, as the energy in the wind is the cube of wind speed [4,74,75] and many others. |
| 2. *Changes in daily or seasonal distribution of wind* | a) It can affect the match between wind energy input to the grid and daily load demand [4,75].<br>b) Seasonal changes can affect the profitability of the plants due to the evolution of price [72]. |
| 3. *Changes in temperature* | a) Increasing air temperatures, as expected with climate change, will lead to slight declines in air density and power output [60,74].<br>b) Drifting sea ice due to ice melting can damage wind turbine foundations offshore [4,60,76] and affect operations at wind farms located in Northern latitudes [74].<br>c) Changes in extreme cold periods can affect output (e.g., through turbine blade icing) [4]. Ice on turbine blades can affect performance and durability [60,77].<br>d) A rise in temperature might increase operational costs and affect the efficiency of the equipment [24,78].<br>e) Extremely low or high temperatures may affect various components of wind farms [60,79].<br>f) Changes in permafrost conditions may affect road construction and repairs for wind farms [74]. |
| 4. *Sea level rise* | a) Sea level rise could damage off-shore turbine foundations in low-lying coastal areas [4] as well as onshore turbines in coastal locations [74]. |
| 5. *Extreme weather events* | a) Any extreme event can damage infrastructure and complicate access [4]. In this regard, hurricanes or storm surges can cause damage to offshore farms [4] and affect the lifespan of wind turbines [74].<br>b) The design of the turbine will be affected by expected turbulence intensity, wind shear and transient wind conditions such as wind speed or directional changes [61,74].<br>c) During extremely high or low wind speeds, farms can be shut down [80]. |
| 6. *Others* | a) Changes in vertical wind shear, directional distribution and turbulence intensity are relevant, but difficult to quantify with existing tools [3,74].<br>b) Large-scale circulation and seasonal patterns such as El Niño/Southern Oscillation may affect wind [68].<br>c) Changes in wave activity may affect structural conditions of offshore farms [60]. |

### 4.2. Main projections in literature

Many studies focus on Europe, and most agree on two questions: (a) there appears to be a north-south divide and (b) aggregated changes do not seem to jeopardize existing developments. Regarding the north-south divide, the general consensus points to an increase in wind energy potential in Northern and Central Europe, and to a decrease in Southern Europe [78,80–84]. Projected seasonality, however, seems to change depending on the model and area.

With respect to aggregated changes, the conclusion of many studies is that wind energy changes will not dramatically affect wind energy development in Europe [60,78,81]. Projected variations depend on the source. Changes in wind energy output can range from +/- 12% depending on the region [80], or +/- 5% with some exceptions [81,83].

However, according to a recent paper [75], the general trend is a reduction in wind energy density. This is particularly relevant during the summer (but also autumn and spring), while an increase is projected in winter in Northern and Central Europe. This decreasing trend was later confirmed [85] in most areas across Europe, except in the Black Sea, where it is expected to remain stable (which is consistent with Reference [86]). A recent paper [30] also projects a reduction of wind power potential in most countries except Greece.

Regarding offshore wind energy in Europe, one study projects a slight decrease in production in most areas of Northern Europe and a clear reduction in the Mediterranean (except southwest of the Iberian Peninsula) [87]. These trends were later confirmed by Reference [78].

The above mentioned north-south divide in Europe is basically consistent with the results of studies at a national level. For the UK, one study projects increases in wind speed for the North Atlantic and North Scotland and a decrease in the English Channel and South England [62]. However, these projections mainly serve to provide a model for an economic evaluation of impacts on the levelised cost of wind energy. Another study projects little variation in mean annual production but relevant changes in seasonality [88], very similar to the projections for Ireland by Reference [89].

For Germany, studies do not seem to find great variations in the projected evolution of the resource [8,35] but one local paper highlights important changes in seasonality [90]. A large increase in wind speed is projected for Croatia, which could have a substantial impact on production [34].

When it comes to the Iberian Peninsula, the decreasing trend mentioned above is confirmed by Reference [91] and by Reference [92] with the exception of the Gibraltar Strait Area. When it comes to offshore wind, the results are similar, with an expected yearly reduction of wind speed and wind energy potential of less than 5% in most areas [69].

Some of the many studies focused on the US predict a reduction in mean wind speed consistent with the negative trend in observed data [67,93], but there is some debate over whether that change is significant and exceeds natural climate variability [65]. More recent papers provide a varied (and divergent) picture of future changes, without providing a global figure for the country [94–96]. There are also some local studies focused on smaller areas [63,97].

Brazil has also received attention in the literature. All existing projections are optimistic in terms of wind speed and generation, especially in the north and northeast, where most production is located, with projected increases between 10-20% [98–100].

Small variations in wind speed are projected for China by the end of the century, no matter the RCP considered [101], even though historical trends suggest a decline [102,103], which has been detected for the Tibetan Plateau as well [104]. Reductions in wind energy density are projected for the Taiwan Strait throughout the 21st century [105].

One study uses a different approach than most papers, estimating production based on projections for temperature and radiation [106]. The forecasted trend predicts a decline in production in various wind farms in Iran.

Africa is the least studied area, probably due to the low development of wind energy generation [13]. Projections for Southern Africa point to almost no change in wind speed, with some seasonal variations [66].

There are also some studies on wave activity, which may be relevant for offshore farms. An increase is predicted for the Northeast Atlantic, the Baltic Sea, the North Sea and the Black Sea, whereas a decrease in wave heights is expected for the Mediterranean [60,107–109]. Wave energy generation will be analysed later in this paper.

Table 4 provides further details of the most relevant studies on this topic.

**Table 4.** Most relevant studies on climate change impacts on wind energy generation.

| EUROPE | | | | | | |
|---|---|---|---|---|---|---|
| **Reference** | **Geographic area** | **Generation source** | **Scenarios** | **Reference period** | **Projection period** | **Projected changes** |
| [30] | *Europe* | Wind (and solar, hydro and thermal generation) | 1.5ºC, 2ºC and 3ºC based on AR5 RCP 4.5 and 8.5 | 1971-2000 | The earliest 30-year period when global mean temperature exceeds 1.5, 2 and 3ºC. | Reductions in wind energy potential are projected in all countries except Greece. Changes do not exceed 5% except in Portugal, Ireland and Cyprus in the 3ºC scenario. |
| [80] | *Europe* | Wind | AR5 RCP 4.5 | 1979-2005 | 2020-2049 | Wind speeds are projected to increase 2-4% in Northwest Europe during the summer and winter (production is expected to increase 4-8%), while decreases of 3-6% are expected for the Mediterranean in the winter (production expected to decrease 6-12% for this area and season). |
| [85] | *Europe* | Wind | AR5 RCP 4.5 and 8.5 | 1979-2004 | 2021-2050 and 2061-2090 | A general decrease in wind power density is to be expected in Europe, except in a few locations. The decrease is constant in RCP 4.5 and 8.5, but of a greater magnitude in the latter. However, no discernible changes are expected in the Black Sea Area. |
| [84] | *Europe* | Wind | 1.5ºC increase (HAPPI Project) | 2006-2015 | Future with 1.5ºC increase | Potential for wind development will increase in Northern Europe and decrease in Southern Europe but will not jeopardize future generation. |
| [75] | *Europe* | Wind | AR5 RCP 4.5 and 8.5 | 1986-2005 | 2016-2035<br>2046-2065<br>2081-2100 | The general trend is a decrease in wind energy density in Europe, particularly in Eastern Europe (except the Baltic Sea) and the Mediterranean. Variations increase over time and are more pronounced under RCP 8.5. A decrease in spring, autumn and especially in the summer is to be expected, while an increase in winter is predicted. |
| [83] | *Europe* | Wind | AR5 RCP 4.5 and 8.5 | 1971-2000 | 2071-2100 | Overall energy production will remain within +/- 5% throughout the 21st century. The greatest reductions are expected for the Iberian Peninsula and Italy. RCP 8.5 projects changes with enhanced magnitude. |
| [81] | *Europe* | Wind | SRES A1B | 1971-2000 | 2031-2060 and 2071-2100 | Changes in wind energy potential are weak or non-significant over a large part of Europe. A decrease is projected for the Mediterranean and an increase on the Baltic Sea. |
| [78] | *Europe* | Wind (and solar PV) | SRES A1B | 1961 | 2050 | An increase in wind speed is projected in Northern Europe and a decrease in the south. |

| | | | | | | |
|---|---|---|---|---|---|---|
| [82] | *Europe* | Wind | SRES A1B | 1961-2000 | 2001-2100 | Regarding wind energy potential, an increase is expected in Northern and Central Europe, particularly in winter and autumn. A decrease is predicted in Southern Europe, expect for the Aegean Sea. Changes in wind energy output follow the same pattern but of a smaller magnitude. |
| [86] | *Black Sea Area* | Wind | AR5 RCP 4.5 and 8.5 | 1981-2010 | 2021-2050 | No relevant differences in wind speed are projected. Both RCPs provide similar results, but 4.5 shows a small decrease and 8.5 a slight increase in most areas. |
| [87] | *Northern Europe* | Wind (offshore) | SRES A1B | 1972-2001 | 2020-2049 | A weak reduction in production is projected in most areas except in the Baltic Sea (-2 to -6%). A clear reduction is projected for the Mediterranean. |
| [35] | *Germany and Austria* | Wind (among others) | SRES A1B | 1971–1989 | 2051–2080 | Small changes for wind are projected in a context where fossil fuel prices are expected to have a higher influence than climate variables. |
| [8] | *Germany* | Wind (among others) | AR5 RCP 2.6 and 8.5 | 1981–2010 | 2015-2050 | For RCP 2.6, small changes and no clear trend in production are to be expected. For RCP 8.5 in southern Germany a decrease of 2% is projected. For the northern parts and some stations in central and southern Germany, an increase of up to 3% is expected. |
| [90] | *Northwest Germany* | Wind (among others) | SRES A1B | 1981-2010 | 2036-2065 and 2071-2100 | Wind speeds decrease in summer and increase in winter. The mean interannual standard deviation from the monthly averages is 12.9% for 2036-2065 and 12.3% for 2071-2100. |
| [62] | *UK* | Wind | AR5 RCP 2.6, 6 and 8.5 | 1981-2000 | 2011-2030, 2041-2060 and 2071-2090 | The North Atlantic area and North Scotland have the greatest increase in wind speed, whilst South England and the English Channel have the greatest decrease. But the model does not represent the current historical distribution of the resource in the UK. |
| [88] | *UK* | Wind | SRES A1B, A2 and B1. | 1961-1990 | 2081-2100 | The seasonal pattern in UK wind is expected to strengthen, with increases in wind speed in winter and decreases in summer. But the overall changes in mean annual productions are likely to be small. |
| [110] | *Two wind farms in Scotland (UK)* | Wind | SRES A1B. | 1971-1990 | 2040 | Wind speed increases in one wind farm and decreases in another. However, projected changes in extractable wind power are small (<+/-3%). Important changes in wind direction are projected. |
| [69] | *Iberian Peninsula (Spain and Portugal)* | Wind (offshore) | AR5 RCP 4.5 and 8.5 | 1971-2000 | 2071-2100 | Most models predict a reduction of wind speed and wind power for all seasons, except summer. Yearly reductions (smaller than 5%) are to be expected in all areas except the northwest coast. |
| [91] | *Iberian Peninsula (Spain and Portugal)* | Wind | SRES A1B | 1961-200 | 2041-2070 | A decrease in wind energy power is projected throughout most of the Iberian Peninsula with the remarkable exception of the Gibraltar Strait. Regarding seasonality, a decrease is projected in winter for most areas. |

| | | | | | | |
|---|---|---|---|---|---|---|
| [92] | *Iberian Peninsula (Spain and Portugal)* | Wind | SRES A1B | 1980-1999 | 2005-2050 | A reduction in wind speed (never higher than 5%) is projected for all analysed clusters except for the Gibraltar Strait. |
| [34] | *Croatia* | Wind (along with solar and hydro) | SRES A2 | 1961-1990 | 2011-2040 and 2041-2070 | A large change in mean wind speed can be expected on the coast and adjacent mainland. For 2070, wind speeds could increase by 50% in the summer. |
| [89] | *Ireland* | Wind | SRES A1B, A2 and B1. | 1961-2000 | 2021-2060 | No substantial changes in wind speed are projected, but an increase in winter and a decrease in summer is to be expected. |
| **AMERICA** | | | | | | |
| **Reference** | **Geographic area** | **Generation source** | **Scenarios** | **Reference period** | **Projection period** | **Projected changes** |
| [95] | *USA* | Wind | SRES A2 | 1968-2000 | 2038-2070 | An increase in wind energy density is projected for most areas of the US. The biggest increase is projected for Kansas, Oklahoma and Texas. |
| [96] | *USA* | Wind (and solar) | SRES A2 | 1985-2005 | 2040-2069 | Changes in wind speed do not exceed +/- 10% and vary depending on the season and geographical area. |
| [93] | *USA* | Wind | AR5 RCP 8.5 | 1979-1999 | 2079-2099 | Changes of small magnitude in mean wind speed and wind direction are projected. An increase is projected in winter in some areas, and a decrease in the summer. |
| [94] | *USA* | Wind | SRES A1B | 1990-1999 | 2040-2049<br>2090-2099 | The average wind speed in the continental US is expected to shift more by mid-century than by the end of the century. The biggest increases are expected in the Great Plains, Northern Great Lakes and southwestern states. |
| [65] | *USA* | Wind | SRES A2 | 1979-2000 | 2041-2062 | There is no statistically significant climate change signal. Natural variability exceeds the climate change signal. |
| [67] | *USA* | Wind | IS92a - IS92d | 1948-1978 | 2025, 2050, 2075, 2100 | One model/scenario projects minimal changes in wind speed. Another projects a reduction in mean wind speed of 10-15%. |
| [63] | *3 windfarms in California (USA)* | Wind | SRES A2 | 1980-2000 | 2051-2071 | Predicted changes do not exceed +/-2% for the locations. Wind speed is projected to increase in the summer. |
| [97] | *Northwest USA* | Wind | SRES A1B and A2. | 1964-2000 | 2050 | Wind power resource is projected to decrease by up to 40% in spring and summer. In winter a smaller reduction may be expected. |
| [100] | *Brazil* | Wind (and solar) | AR5 RCP 4.5 and 8.5 | 1961-1990 | 2021-2050<br>2070-2099 | An increase in wind speed and wind power is projected in most of the country, especially in the northern region. In the Northeast, where most production is currently located, average wind speed is expected to increase by 9.4%. |
| [99] | *Brazil* | Wind | SRES A2 and B2 | 1962-1990 | 2010-2040<br>2040-2070 | 15-30% growth in wind power density is projected for most of the Northeast, with the biggest increase in the autumn (March-May). |

| | | | | | | |
|---|---|---|---|---|---|---|
| | | | | | 2070-2100 | |
| [98] | *Brazil* | Wind | SRES A2 and B2 | 1961-1990 | 2071-2080<br>2081-2090<br>2091-2100 | Wind speed is projected to increase in most areas of the country, with an average increase of 20% in the Northeast. The average capacity factor of wind generation is predicted to increase from 17% to 19-21% by the end of the century. |
| **ASIA** | | | | | | |
| **Reference** | **Geographic area** | **Generation source** | **Scenarios** | **Reference period** | **Projection period** | **Projected changes** |
| [101] | *China* | Wind | AR5 RCP 4.5 and 8.5 | 1971-2005 | 2066-2100 | Spatial distribution of mean wind speeds seems very similar under both RCP2. |
| [105] | *Taiwan Strait* | Wind | ECHAM5<br>CM2.1<br>CGCM2.3.2 | 1981-2000 | 2011–2040<br>2041–2070<br>2071–2100 | A reduction is projected of up to 3% wind energy density. The reduction will be constant throughout the 21st century. |
| [106] | *13 stations in Southwest Iran* | Wind | SRES A1B and A2 | 1987-2009 | 2046-2065 | A decrease in production is predicted in almost all cities, with variations of +/- 10%. |
| **AFRICA** | | | | | | |
| **Reference** | **Geographic area** | **Generation source** | **Scenarios** | **Reference period** | **Projection period** | **Projected changes** |
| [66] | *Southern Africa* | Wind (alongside with PV) | SRES A2 and B1 | 1979-2009 | 2045-2055 | Small changes in wind speed are projected by 2050, but seasonal variations may be relevant. |

## 5. Solar generation

### *5.1. Main impacts and methodological issues*

In 2017, solar PV was the technology with the greatest contribution to new installed capacity (at least 98GW) [13]. The countries with the most installed capacity of solar PV are China, the United States, Japan, Germany and Italy. The total installed capacity is 402 GW. Concentrating solar thermal power provides a more modest 4.9 GW. If the climate goal of 2ºC is to be achieved, solar PV should evolve from around 1% of total electricity generation in 2015 to 22% in 2050. That would mean an investment of roughly 5 trillion USD until 2050 in solar PV generation, and around 2 trillion USD in concentrated solar power [1].

The levelised cost of solar PV has decreased dramatically from 0.36 USD/kWh in 2010 to 0.10 in 2017, whereas concentrated PV still costs an average of 0.22 USD/kWh [15]. Even if high initial investment costs constitute an important barrier for the upscaling of solar generation technologies [111], the technology allows for smaller installations with lower capital costs than hydro or wind, which may reduce the relative importance of climate impacts. The shorter life span of a PV panel (around 20 years) compared to other technologies may also be relevant in this regard [4].

As a result, literature on climate change impacts on solar sources has received less attention than that on wind or hydro [5,112]. This is also due to the high uncertainty of the projections [66]. Depending on the model and assumptions, differences in results can be substantial [66,113].

All sources of solar energy are sensitive to climate change [3], but existing literature focuses mainly on photovoltaic generation (PV) and on changes in solar irradiation, as it is the most relevant source [13]. However concentrating solar power (CSP) and solar thermal can be affected by similar variables as well [114,115].

Other variables that can affect solar generation are usually mentioned but seldom quantified, which may lead to an underestimation of their importance [116]. However, one study provides a specific estimate for the impact of aerosols [117]. Variables such as air temperature or wind speed are considered in many papers as well. The role of ocean-atmospheric oscillations (such as El Niño Southern Oscillation) has received less attention [118].

Most papers focus on changes in the resource, without quantifying changes in production or economic impacts. Only Reference [119] quantifies the impacts of climate change on the levelised cost of energy (LCOE).

The main climate threats and expected impacts on solar PV generation are shown in Table 5.

**Table 5.** Main threats and impacts on solar PV.

| CLIMATE THREATS | IMPACTS |
|---|---|
| 1. *Changes in mean temperature* | a) An increase in global temperature would negatively affect the efficiency of the cells and therefore the power output [120–125]. The efficiency of PV modules drops by about 0.5 % for every 1 °C increase in temperature [114].<br>b) An increase in temperature would lower the capacity of underground conductors and increase soil temperature [4].<br>c) An increase in temperature might increase operational costs and affect the efficiency of the equipment [24]. |
| 2. *Changes in solar irradiation and cloudiness* | a) Changes would affect solar power output [78,112,113,125–129]. Concentrated solar power would be more affected as it cannot use diffuse light [3]. |
| 3. *Changes in dirt, dust, snow,* | a) An increase in these variables would decrease energy output [78,116,117,122,125,128,130,131]. |

| CLIMATE THREATS | IMPACTS |
|---|---|
| *atmospheric particles and others* | |
| 4. *Wind speed* | a) Changes in surface wind velocity may affect photovoltaic production [124,125]. Strong wind may cause material damage from debris and need for cleaning [114,115], but they can also cool down the modules, increasing efficiency and output [4]. |
| 5. *Precipitation* | a) An increase would wash away dust but reduce efficiency (less solar radiation) [4].<br>b) Availability of water may affect concentrated solar [132,133]. |
| 6. *Extreme weather events* | a) Extreme weather events may cause damage to PV panels [90].<br>b) Fires and extreme winds can also damage the PV infrastructure [34].<br>c) Sand and dust deposition caused by extreme winds results in reduced power output. Hailstones can also damage PV panels [3,114].<br>d) Heat waves result in reduced output (due to temperature increase) and potential material damage [3,114,115]. |

### *5.2. Main projections in literature*

Various studies analyse global changes in irradiation and its consequences for solar generation. These studies are not easy to compare, as the conclusions are often focused on specific areas of the world and cover different timeframes and scenarios. Reference [126] projects an increase in PV output in Europe and China, as well as a decrease in the western US and Saudi Arabia. Also, according to this study, Europe would be the biggest winner in terms of concentrated solar power, with increases of more than 10% in output. China, Algeria and Australia will also experience increases in output, whereas the western US and Saudi Arabia can expect a decline.

Another study analyses the changes in eight regions of the world [129]. The biggest positive changes in production are again forecasted for Europe, with increases in Spain and Germany (annual increases up to 0.5% for 2049 compared to 2006) and significant reductions in the north of India and Northwest China (annual reductions up to 0.5%).

Reference [128] suggests a global reduction in direct normal irradiation of 5%. The biggest increases are once again expected in Europe (up to 10%), and the greatest reductions in Africa (up to 10%).

Some papers are not as optimistic about the evolution in Europe [30,124], despite a positive trend in irradiation in Southern Europe. Considering expected changes in wind speed and temperature, the results show a decline in generation or potential in most regions, although this does not pose a great risk to mean production. Results are consistent with other studies projecting declines in production in northern countries [127].

This trend is also seen inanother study, which shows a decline in productivity in Eastern Europe and Northern Africa (up to 7%), and an increase in Western Europe and the Eastern Mediterranean (up to 10 %) [78].

Impacts on solar generation have received little attention in the US, even in specific official reports [134]. One study reports potential decreases in production in the western US, but only considers changes in air temperature, not irradiation [135]. More recently, some authors projects variable changes in irradiation across the country of up to +/- 10% [96]. The biggest changes are expected in the winter.

With respect to Africa, the trend projected by Reference [112] points to a decrease in PV output for Western Africa, consistent with the trend mentioned above. Another study projects seasonal changes for Southern Africa, with a trend towards more irradiation in the winter and less in the summer [66]. However, both studies acknowledge high uncertainty in their estimates and do not provide an absolute projection.

When it comes to studies for specific countries, one paper uses various models to analyse Greece [130]. The results mainly indicate an increase in output, except in some areas such as Attica and Thessaly. The results are mainly positive in terms of irradiation in the UK as well, except in some small areas in the northwest [131]. In Germany, one study only projects very small seasonality changes [35]. For Croatia, the trend projected by Reference [34] is neutral due to the balance of opposing impacts (an increase in the mean temperature, a decrease in mean cloud cover, and more frequent extreme weather conditions).

Some studies are more locally focused. For example, Reference [125] and [90] do not suggest relevant overall changes in the Canary Islands or Northwest Germany, but seasonality could be an issue in both areas.

Table 6 provides further details of the most relevant studies on this topic.

**Table 6.** Most relevant studies on climate change impacts on PV generation.

<table>
<tr><th colspan="7">GLOBAL OR REGIONAL</th></tr>
<tr><th>Reference</th><th>Geographic area</th><th>Generation source</th><th>Scenarios</th><th>Reference period</th><th>Projection period</th><th>Projected changes</th></tr>
<tr><td>[128]</td><td>*Worldwide*</td><td>Solar PV</td><td>SRES A1B</td><td>1995-1999</td><td>2035-2039</td><td>A 5% global reduction in direct normal irradiation is projected. The biggest increases are expected in Europe (up to 10%), and the most significant reductions in Africa (up to 10%).</td></tr>
<tr><td>[129]</td><td>*Worldwide (8 regions)*</td><td>Solar PV</td><td>AR5 RCP 4.5 and 8.5</td><td>2006-2015</td><td>2006-2049</td><td>Only Germany and Spain are projected to increase PV production. North-West China and India are likely to face declining energy outputs.</td></tr>
<tr><td>[126]</td><td>*Worldwide*</td><td>Solar PV CSP</td><td>SRES A1B</td><td>1980–1999</td><td>2010 to 2080</td><td>PV: Increases in output are projected in Europe and China, and no significant changes in Algeria and Australia. A decrease is expected in the western US and Saudi Arabia.<br>CSP: output is likely to increase in Europe (>10%), China, Algeria and Australia. A decrease is likely in the western US and Saudi Arabia.</td></tr>
<tr><td>[78]</td><td>*Europe and Africa*</td><td>Solar PV (and wind)</td><td>SRES A1b - B2</td><td>1991-2010</td><td>2030-2050</td><td>A significant reduction in PV productivity is projected in Eastern Europe, and Northern Africa (up to 7%), while an increase is observed in Western Europe, and the eastern Mediterranean (up to 10%).</td></tr>
<tr><td>[117]</td><td>*Europe and Africa*</td><td>Solar PV</td><td>SRES B2</td><td>2000</td><td>2030</td><td>A reduction in productivity is observed in Eastern Europe and Northern Africa (up to 7%), while an increase is seen in Western Europe and the eastern Mediterranean (up to 10%).</td></tr>
<tr><th colspan="7">EUROPE</th></tr>
<tr><th>Reference</th><th>Geographic area</th><th>Generation source</th><th>Scenarios</th><th>Reference period</th><th>Projection period</th><th>Projected changes</th></tr>
<tr><td>[30]</td><td>*Europe*</td><td>Solar (and wind, hydro and thermal generation)</td><td>1.5ºC, 2ºC and 3ºC based on AR5 RCP 4.5 and 8.5</td><td>1971-200</td><td>The earliest 30-year period when global mean temperature</td><td>Moderate reductions in photovoltaic power potential are projected in most countries expect for Portugal, Spain, Greece and Cyprus. Changes are smaller than 5% except in Baltic countries, Finland and Sweden for the 3ºC scenario.</td></tr>
</table>

| | | | | | | |
|---|---|---|---|---|---|---|
| | | | | | exceeds 1.5, 2 and 3ºC. | |
| [113] | *Europe* | Solar (radiation) | AR5 RCP 8.5 | 1971-2005 | 2006-2100 | GCMs project an overall increase in radiation. Regional Circulation Models (RCMs) project a global decrease. |
| [124] | *Europe* | Photovoltaic | AR5 RCP 4.5 and 8.5 | 1970-1999 | 2070-2099 | Under the RCP 8.5, irradiation increases in the southern Mediterranean regions and decreases in northern areas. There is an intermediate area where the change is less robust. However, a decline in PV production is seen in almost all regions, reaching 10-20% in Scandinavian countries. |
| [35] | *Germany and Austria* | Solar PV (among others) | SRES A1B | 1971–1989 | 2051–2080 | Small changes in seasonality are projected for solar PV in a context where fossil fuel prices are expected to have a higher influence than climate variables. |
| [130] | *Greece* | Photovoltaic | AR4 A1B scenario | 1985-2005 (for irradiance) | 2011-2050 and 2061-2100 | Average increases in photovoltaic output for all regions are projected, except for Attica and Thessaly. Increases are around 1-2% in the first period and 2-3% in the second period. |
| [131] | *United Kingdom* | Photovoltaic | Low, Medium and High scenarios of the UK Climate projections UKCP09. | 1961-1990 | 2040-2069, 2070-2099. | Irradiation will increase on average in most areas of the UK, while marginally decreasing in the northwest. The overall effect is a mean increase of the UK solar resource. |
| [90] | *Northwest Germany* | Solar PV (among others) | SRES A1B | 1981-2010 | 2036-2065 and 2071-2100 | A seasonal change in solar irradiation has been projected but expected changes in production are not significant. |
| [34] | *Croatia* | Solar (along with hydro and wind) | SRES A2 scenario | 1961-1990 | 2011-2040 and 2041-2070 | There is a neutral trend for solar PV due to opposing forces: positives (greater solar irradiance and less snowfall) and negatives (increase in temperatures, severe weather and extreme conditions). |
| [125] | *Canary Islands (Spain)* | Solar PV | AR5 RCP 4.5 and 8.5 | 1995-2004 | 2045-2054 and 2090-2099 | Mean annual changes in irradiation are not relevant. An increase in PV potential is expected during the winter because of reduced cloud cover. During the summer, a decrease is projected due to the rise in temperature |
| [127] | *Nordic Region (various cities)* | Solar PV (among others) | SRES A2 and B2 | 1961–1990 | 2071–2100 | A reduction in irradiation is projected for all cities. Reductions can be up to 16% in the A2 scenario for Helsinki. Increases in temperature are also projected, which will increase the negative effects in production |

| **AFRICA** | | | | | | |
|---|---|---|---|---|---|---|
| **Reference** | **Geographic area** | **Generation source** | **Scenarios** | **Reference period** | **Projection period** | **Projected changes** |
| [66] | *Southern Africa* | Solar PV (along with wind) | SRES A2 and B1 | 1979-2009 | 2045-2055 | By 2050, small changes in irradiance are projected. In winter, the median shows predominantly increased irradiation, while in the summer a decrease is predicted for most of the region. |
| [112] | *West Africa (15 countries)* | Solar PV | AR5 RCP 8.5 | 2006–2015 | 2006–2100 | Climate change will lead to decreasing PV output for all countries except Sierra Leone (minimal increase), due to a reduction in irradiation and an increase in temperature. |
| **AMERICA** | | | | | | |
| **Reference** | **Geographic area** | **Generation source** | **Scenarios** | **Reference period** | **Projection period** | **Projected changes** |
| [96] | *USA* | Solar (and wind) | SRES A2 | 1985-2005 | 2040-2069 | Changes in irradiation do not exceed +/- 10% and vary depending on the season and geographical area. Spring and autumn tend to show more negative trends than winter and summer. |

## 6. Other renewable sources

This section will address climate change impacts on other renewable generation sources. A table providing further details on studies on them has been included in the appendix.

### 6.1. Biomass generation

The effect of climate change on biomass generation has received little attention, as it has been considered within the climate change impacts on agriculture and forestry. As a result, there are no specific estimates of how climate change could affect biomass for electricity generation worldwide. It seems reasonable to assume that most of the impacts will be related to agriculture and forestry, not to waste or animal farming [136]. Regarding crops connected to food production, there is high confidence in the existence of impacts [137]. These impacts depend on specific crops and latitudes, but generally negative impacts are more common than positive ones [137]. The main climate threats and impacts on biomass generation are shown in the appendix.

There are many studies focused on specific types of plants and crops. Therefore, the results of these studies are highly regional and variable depending on the crops and areas of study [136]. General country level impact studies (such as Reference [138]) usually address agriculture and forestry and therefore can serve as a useful reference. In any case, there is very high uncertainty regarding the representation of carbon dioxide, nitrogen and high temperature effects [137,139]. The quantification of the impacts of extreme events on cropping systems is also hard to nail down [137].

A general study for bioenergy crops [140] projects an increase in global availability if farmers are able to benefit from $CO_2$ fertilization (higher concentrations). Otherwise, a reduction is projected for most areas. For Europe, all energy crops are predicted to increase in Central and Northern Europe, but decrease in the Mediterranean and the Pannonian Basin [141].

Regarding boreal forests, climate change seems to have a positive influence overall [142], despite extreme events [143]. This trend for forests has also been found in Germany by one study that highlights potential negative impacts for straw and maize [144]. Risks for energy crop cultivation used for biofuel and biogas in the country have also been analysed [145].

When it comes to sugarcane, a qualitative study predicts negative impacts by mid-century [146]. However, results for Brazil show an increase in sugarcane production due to climate change and a decrease in biodiesel [49]. Positive impacts are expected for energy cane in the US as well according to one study [147], which does not project negative impacts on energy crops generally speaking. Other paper shows a negative correlation between maize production and very high temperatures [148], which may be exacerbated by climate change.

### 6.2. Wave energy

There is some recent research on climate change impacts on wave energy generation. All technologies based on marine water could potentially be affected by changes in water temperature, temperature gradients, salinity, sea level and wind patterns [7,149]. One pioneer paper [150] suggests that wave energy would be very vulnerable to climate change due to variations in wind forces. Recently, more sophisticated approaches and scenarios have been used to project wave energy in the UK and Menorca [151,152] with inconclusive results.

### 6.3. Geothermal generation

In terms of geothermal generation, most of the impacts are shared with other generation sources (water availability, damages to infrastructure, flooding and an increase in ambient temperature) [4,7]. No specific quantitative papers with projections have been found for this source.

## 7. Discussion

The impacts of climate change on renewable energy make up a growing area of research. Many studies have been conducted in the past few years, especially on hydropower and wind energy. The studies included in this paper do not constitute a perfect sample of all existing studies, as more recent papers have been prioritized in the most studied areas. But based on this information, there is a clear increase in research, as nearly half of the included references are from 2015 or later.

The sectoral and geographical scope of the studies analysed in this paper can be seen in Figure 1 and Figure 2. There is a clear preponderance of papers focused on hydro and wind compared to other technologies. Recently, many papers have focused on one geographical area and compared the impacts on multiple technologies.

From a geographical standpoint, Europe is by far the most studied area, and there is a clear north-south divide in the projections. The north is expected to experience mainly positive impacts on wind, hydro and biomass, whereas impacts on these technologies in the south are projected to be negative. The opposite may be the case when it comes to solar energy. In the US, studies tend to show diverse and often inconclusive results across the country for all technologies. In other parts of America, except Brazil, more studies are needed to provide a comprehensive view.

In Asia and Africa, results also differ depending on the technology and area. Many parts of Asia are expected to see an increase in hydropower potential, whereas the effects on solar and wind could be negative in various regions. More research should be carried out in Africa, as only some areas and technologies have been studied.

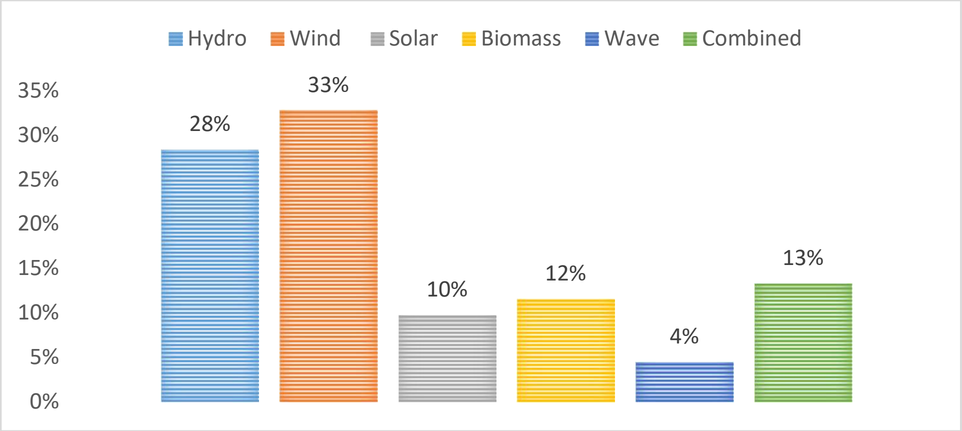

**Figure 1.** Technological scope of analysed papers.

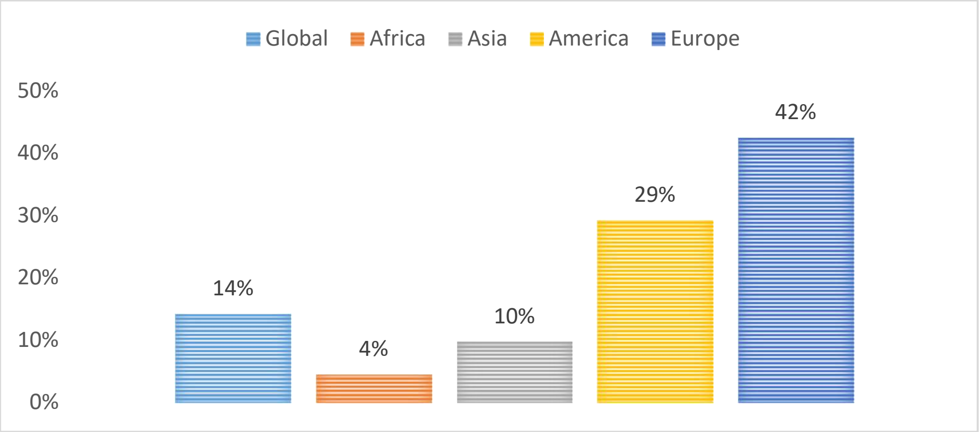

**Figure 2.** Geographical scope of analysed papers.

Uncertainties are highly relevant and stem from multiple variables. First, it is not possible to attach a probability of occurrence to any climate scenario or to the underlying concentration scenarios [17]. Second, global papers mainly use GCMs, whereas more recent and local papers tend to use RCMs, which better represent local conditions of atmospheric flows and weather [153]. The number of models used differs, but most use a multi-model ensemble of those that best fit historical data.

Lastly, there are many other variables that have an influence on the development of renewable energies in the long term. As a result, economic estimates are infrequent and mostly present in global assessments or in specific studies focused on hydropower, due to the magnitude of potential impacts. These estimates focus on the economic implications for investments (such as [48]), GDP (such as [47]) or operating margins (such as [19]). In any case, the impacts can be highly relevant. For example, Reference [154] focuses on just a few impacts from the supply side and on changes in demand, and predicts a 14% (51 billion USD) increase in costs for the US electricity system for 2050, under a no mitigation scenario.

Thus, further research should include more variables in the analysis, particularly economic variables and adaptation measures. Changes may take place over decades and investors and policy makers will have some time to adapt, depending on technology, capital costs requirements, or the legal framework. Furthermore, the evolution of some technologies may influence others and the market. Conflicts with other users of the resource can be a key variable as well when it comes to hydroelectric power.

As a final remark, useful conclusions can be drawn from these studies for the development of public policies, as well as for private investment strategies. Despite the above-mentioned uncertainties, these projections provide the most accurate estimates for decision making in these areas and will be improved by further research. Some technologies and areas are so vulnerable that not considering these projections could jeopardize investments and put the electricity supply at risk.

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## APPENDIX. CLIMATE CHANGE IMPACTS ON BIOMASS GENERATION AND MOST RELEVANT STUDIES ON OTHER SOURCES OF GENERATION

**Table 7.** Main threats and impacts on biomass generation.

| CLIMATE THREATS | IMPACTS |
|---|---|
| 1. *Changes in precipitation* | a. An alteration in rainfall patterns may affect growing conditions and the production of biomass [4,67].<br>b. A reduction in water availability may generate problems for production [136], including cooling water operations [6].<br>c. Changes in precipitation would also affect moisture content of feedstock, lowering energy content [4].<br>d. Changes in seasonality (of rain or temperature) may also affect crops [136]. |
| 2. *Extreme events* | a) Storms, cyclones and flooding may affect production of crops [4,136].<br>b) Extreme events may affect production infrastructure, as well as storage facilities [4,149].<br>c) Frosts and storms can affect productivity [143]. |
| 3. *$CO_2$ concentration in the atmosphere* | a) Concentration may be positive for some quick-growing varieties and $C_3$ plants but negatively affect others [4,143,146,149]. |
| 4. *Increase in temperature* | a) An increase in temperature might affect growing conditions and increase operational costs and affect the efficiency of the equipment [24,67,143].<br>b) An increase in temperature would affect the thermal generation efficiency [6]. |
| 5. *Other* | a) Changes in solar irradiation may affect growing conditions [67].<br>b) A combination of these variables may change the prevalence of pests and fires [136].<br>c) Climate change may indirectly affect ecosystem services, such as pollination services [146]. |

**Table 8.** Most relevant studies on climate change impacts on other renewable sources of generation.

| **GLOBAL OR REGIONAL** | | | | | | |
|---|---|---|---|---|---|---|
| **Reference** | **Geographic area** | **Generation source** | **Scenarios** | **Reference period** | **Projection period** | **Projected changes** |
| [140] | *Global* | Biomass | SRES A1B, A2, B1 | 1996-2005 | 2046-2055 | An increase in bioenergy potential is projected if a "CO2 fertilization" effect is considered (due to higher concentration). Otherwise, results are basically negative for all areas except Central Asia, Russia and Western Europe. Food requirements for a growing population and feed for livestock can strongly influence this potential. |
| **EUROPE** | | | | | | |
| **Reference** | **Geographic area** | **Generation source** | **Scenarios** | **Reference period** | **Projection period** | **Projected changes** |
| [141] | *Europe* | Biomass | SRES A2 | 2003-2007 | 2020-2030 | An increase in the annual growth rate of bioenergy crops has been projected in all areas, except in the Mediterranean and the Pannonian Basin. The negative effects can be mitigated with technological improvements. In any case, total biomass production may not be enough for the EU objectives on this topic. |
| [141] | *Kronoberg County (Sweden)* | Biomass | AR5 RCP 4.5 and 8.5 | 1986-2005 | 2081-2100 | Climate change is projected to speed up forest growth, especially under RCP 8.5. The impact is dramatically reduced by the projection of major storms, but there is still growth compared to the historic period. |
| [142] | *North-Central Sweden* | Forest production | SRES A2 and B2 | 1961-1990 | 2010 to 2109 | Forest production is projected to increase by 33% over 100 years. This will imply a net reduction in carbon emissions of up to 104 Tg over 100 years. |
| [144] | *Germany* | Biomass (forest, short-rotation coppices, maize, straw) | IPCC's AR5 RCP 8.5 | 1981-2010 | 2031-2060 | Climate change does not pose a great danger to bioenergy targets in Germany, if disturbance and extreme events are not taken into account. The effect on forests and short-rotation coppices is mainly positive, but negative on straw and maize. |
| [151] | *Cornwall, UK* | Wave Energy | SRES A1B and B1 | 1961-2000 | 2061-2100 | Available wave power is projected to increase by 2-3% in the A1B scenario and to fall by 1-3% in the B1 scenario. |
| [152] | *Menorca, Spain* | Wave Energy | SRES A1B | 1971-2000 | 2071-2100 | 3 models project wave energy reduction, while 2 others predict an increase. The ensemble average would predict a reduction of between 2.5% and 6%. |

| AMERICA | | | | | | |
|---|---|---|---|---|---|---|
| **Reference** | **Geographic area** | **Generation source** | **Scenarios** | **Reference period** | **Projection period** | **Projected changes** |
| [147] | *USA* | Energy crops | AR5 RCP 4.5 and 8.5 | 1950-2000 | 2041-2060<br>2061-2080 | Climate change impacts are compensated by the geographical and climate diversity of the country and as a result are not necessarily a threat to biomass production. Positive impacts are projected for energy cane and lowland switchgrass, whereas upland switchgrass and willow experience modest reductions. |
| [49] | *Brazil* | Biomass (and hydro) | SRES A2 and B2 | 2007 | 2080. 2090. 2100 | Climate change will positively impact the production of sugarcane, with an increase in output of 161%. The country's main producing regions will continue to be within the temperature limits for sugarcane. On the contrary, the production of biodiesel could be negatively affected, especially castor bean due to increases in drought and temperature. |

# The Impact of Climate Change on the Generation of Hydroelectric Power—A Case Study in Southern Spain[1]

Abstract: Climate change could pose a significant threat to the energy sector in various countries. The objective of this study is to analyze the long-term impact of changes in precipitation and water availability on hydroelectric production. To do so, the study focuses on three hydroelectric power plants in Southern Spain combining climatological, technical and economic data and projections. A physical model has been designed that reproduces the plants' operations and incorporates various scenarios for the evolution of contributions to the basin. The results predict a 10 to 49% drop in production by the end of the century, depending on the plant and scenario. This decrease in production, in accordance with our economic and operational hypotheses, would significantly affect the operating margins of the facilities and, in certain scenarios, could reach an economically unsustainable level by the end of the century. An investment analysis has been carried out as well, showing that climate change may jeopardize future investments in similar facilities.

Keywords: climate change; climate change adaptation; hydropower generation; water resources; renewable energy

## 1. Introduction

The energy sector is responsible for two-thirds of anthropogenic greenhouse gas emissions globally [1] and, therefore, is a very relevant contributor to climate change. At the same time, the impacts associated with this phenomenon may jeopardize the existence of a secure energy supply [2].

Within the sector, electricity generation may be impacted by, among other factors, rising global temperatures, changes in the frequency and intensity of extreme weather events, changes in air temperature, and most notably, changes in rainfall patterns. These impacts will have repercussions throughout the sector's value chain, including the provision of raw materials, energy generation itself, and supply and distribution, and will occur in one form or another in nearly all energy generation technologies [3–5].

Despite the extent and importance of these effects, the sector has limited coverage in the principal studies developed in the field, as well as in the deployment of investments and adaptive measures [6]. Nevertheless, papers are beginning to emerge that offer an overview of the potential impacts on electricity generation technologies or in different geographic areas [7–9]. However, there is less available literature that presents a detailed analysis of specific projects or plants, or that analyzes the economic implications of climate change or how it can influence new investments in the sector [10]. A multidisciplinary approach is necessary so that economic, physical and regulatory issues are considered together.

In the case of hydroelectric power, apart from the sector's overall vulnerability, the impacts on its primary resource, water, must be taken into account. By its very nature, hydroelectricity is sensitive to variations of this resource, both in terms of average rainfall patterns and relative changes in frequency and intensity [11]. In view of the existing literature, it is estimated that there will be significant local variations in hydroelectric generation, with greater generation in high latitudes and humid tropic regions, and less in middle latitudes and dry tropic regions [12]. According to available information, these variations will be compensated on a global level, with no large fluctuations

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expected in the technology's total energy generation as a consequence of climate change by 2050 [12,13].

The south of Europe, Spain in particular, are among the regions that can expect a more significant decrease in the resource. According to the Intergovernmental Panel on Climate Change [14], runoff can decrease by 6 to 36% up to the 2070s compared to the period 1961–1990. In this regard, the Spanish government's National Climate Change Adaptation Plan [15] and its successive working programs include industry, energy and water resources among the vulnerable sectors.

The objective of this study is to combine physical, technical and economic information to analyze to what extent a decrease in average rainfall and changes in temperature, as a consequence of climate change, could affect the long-term profit margins and operations of a hydroelectric plant. Therefore, the aim is to provide a multidisciplinary analysis combining climate data, technical calculations for electricity production and an economic assessment of the implications for utilities, energy planners and policy makers. The analysis has benefited greatly from the collaboration of several departments within the company that operates the power plants.

Accordingly, this paper is structured as follows: the next section gives a description of the plants and an overview of the methodological basis and the model. Section 3 presents the key assumptions of the projection and summarizes the most important results in terms of future production. Section 4 analyzes the economic implications of the projections, in terms of profitability and investments. Section 5 provides some insights on the discussion of the results in the context of climate change policy. The paper closes with some concluding remarks.

## 2. Methodology

### 2.1. Description of the Plants

Over the years, the company ENDESA (Madrid, Spain) has worked to better evaluate its vulnerability to climate change. In 2012, it conducted a broad study, internally and confidentially, that analyzed the vulnerability of its power plants worldwide, which included all utilized technologies. As a result of this top-down assessment, several businesses and countries were identified as hot spots for further analysis, including hydroelectric generation in Spain.

In 2014, as part of the Adapta initiative, coordinated by the Spanish Office of Climate Change, a multi-criteria study was conducted of three hydroelectric power plants. In that study, different climate impacts were considered and evaluated. In conclusion, the most relevant impacts identified were a rise in temperature, a decrease in rainfall, and the intensification of extreme rainfall events [16].

The same plants have been selected for this study, as their varied characteristics provide a good example of how climate change may impact each distinct type of plant. The most significant characteristics are outlined in Table 1.

The first two plants have considerably less operational flexibility in their management. Mengíbar, as a run-of-river plant, has hardly any water storage capacity and, when flow is high, it is forced to spill water without utilizing it. Cala, on the other hand, has a storage reservoir of limited capacity and is therefore forced to periodically release water so as not to exceed the hazard curve. Finally, Tranco de Beas has a greater storage capacity, in fact, it is considered unlimited in modeling, and manages water contributions to the basin over the course of several years, with the objective of optimizing energy production. However, the holder of the plant, the Guadalquivir Water Confederation, establishes strict limits on water usage during shortages.

**Table 1.** Characteristics of the analyzed plants. Source: ENDESA.

| Name | Year of Construction | Location | Installed Capacity | Plant Type | Remuneration |
|---|---|---|---|---|---|
| Cala | 1927 | El Ronquillo (Seville) | 12.8 MW | Storage plant, annual balancing | Market price |

| Name | Year of Construction | Location | Installed Capacity | Plant Type | Remuneration |
|---|---|---|---|---|---|
| Mengíbar | 1918 (Refurbished in 1975) | Mengíbar (Jaén) | 4.2 MW | Run-of-river | Market price |
| Tranco de Beas | 1953 | Sierras de Cazorla Natural Park, Segura y Las Villas (Jaén) | 39.8 MW | Storage plant, multiyear balancing | Market price |

All the plants are situated on different locations along the Guadalquivir River Basin, as shown in Figure 1. The Guadalquivir is one of the longest rivers in the Iberian Peninsula. Tranco de Beas, the largest plant, is located near the river source in the province of Jaen. Mengíbar, the run-of-river plant, is located near the middle course of the Guadalquivir in the same province. Cala is located along the course of Rivera de Cala, a tributary of the main river, in the province of Seville. All the plants have higher runoff in winter (ranging between 58% and 37% of the annual runoff) with Mengíbar showing less reductions during the summer.

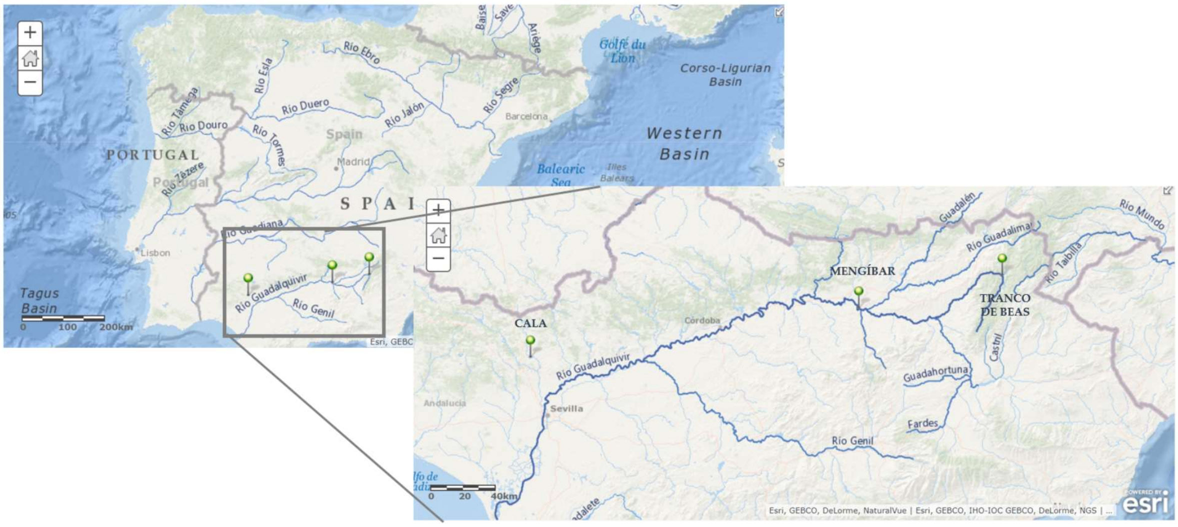

**Figure 1.** Location of the three plants along the Guadalquivir Basin.

The company has provided information on daily water flow, rainfall, and monthly electricity production. While this varies by plant, the information is only considered complete since the end of the 1960's. The SAIH (Automatic Hydrologic Data Collection System, of the Ministry of Agriculture, Food and Environmental Affairs) offers detailed information on many parameters for each location, but only since the year 2000. The historical information is considered adequate and consistent, and no adjustments have been made to it.

### *2.2. The Physical Model*

A model (the Hydroclim model) has been constructed to evaluate the impact on the three hydroelectric power plants operated by the company ENDESA, as described in the previous subsection. Historical data have been collected from both the company as well as public sources. Said data have been used to reproduce the operations of each plant with the model, calibrating it to offer the most accurate results possible. The methodology is explained below.

The model was subsequently used to better understand the impact of the projected evolution of water resources on the plants, based on studies carried out by the Public Administration in Spain. Separately, an economic model has been created to determine to what extent changes in production may impact the plants, both in terms of operating margins and investment.

A *ceteris paribus* approach has been used, in which unitary costs and electricity prices are constant over time. Likewise, it has been assumed that the physical characteristics of the plants have not changed, nor have they taken any adaptive measures, apart from those stemming from their current operating systems.

The reason for this approach, bearing in mind the broad time range of the projections (2011–2100), is to avoid distortion in the analysis, derived from assumptions on future electricity market prices, or the evolution of costs. Similarly, by placing the analysis in operational margins, the impact of discount rates is avoided over such a long period. However, a discount rate has been considered in the investment analysis.

Simulations have been carried out through the model, developed specifically for this purpose. The model reproduces the physical operations of hydroelectric power plants, and is able to generate production outputs from daily flow data. A regression analysis between runoff and production for the same purpose (such as the one conducted in [8]) was conducted also but an engineering approach provided more accurate results, specifically in the plants with bigger reservoirs. This approach is also closer to the actual operation of the plants and to the decision making procedures in the sector.

This model takes into account the distinct characteristics of each plant, through a series of elements:

- Physical parameters, such as the storage capacity of a reservoir, if any, or the plant's net head.
- Technical parameters, like the turbine power and discharge and efficiency factors.
- Operational elements such as the operating regime and external constraints.

The model can therefore be used for both storage and run-of-river plants, and accommodates daily, annual, and multiyear balancing regimes. Additionally, through external constraints, further limitations may be included. In the case of the pilot plants, the limitations are related to usage restrictions due to the need to store water for future agricultural use. Figure 2 provides a schematic description of the model.

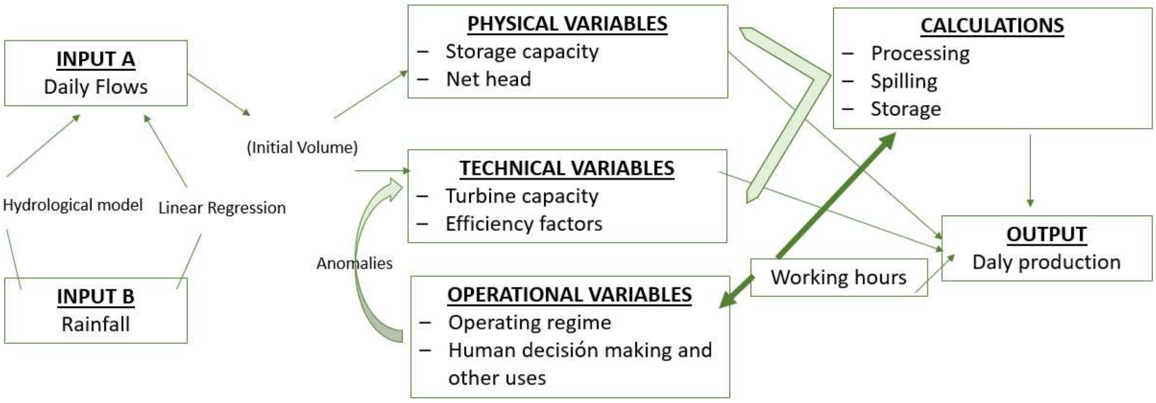

**Figure 2.** Operation of HydroClim Physical Model.

From daily runoff data, the model calculates the daily flow that runs the turbines, spilling (water discharged directly into the river bed, and therefore not exploited), cumulative flow, and operating hours.

Daily production is calculated using the following formula [13,17]:

$$E_t = \gamma \cdot T_t \cdot Hn \cdot QT_t \cdot ef \cdot \mu,$$

where:

- $\gamma = 9.81\ \mathrm{kN/m^3}$ (specific weight of water).
- $T_t$ is the average daily operation time (in hours) in day $t$.
- $H_n$ is the plant's net head (in m).

- $QT_t$ is the flow that runs the turbines in day *t* (in m$^3$/s).
- *ef* is the plant's aggregate efficiency factor, which always takes a value between 0 and 1.
- $\mu$ refers to contingencies. As the goal of the study is to provide future projections that are consistent with the historical performance of the plants, this parameter as well as the efficiency factor have been calculated for each plant and are considered together and assumed to remain constant in the future.

The variable $T_t$ is obtained in the following way:

For each plant, the following data are known:

- $\bar{Q}$, which is the historic average flow to the plant (in m$^3$/s).
- $\bar{Q} = \frac{\sum_{t=1}^{N} Q_t}{N}$, where $Q_t$ is the average flow to the plant in day $t$ (in m$^3$/s), and $N$ is the number of days.
- $\bar{T}$, which is the historic average of operating hours per day.

In the model, it is assumed that in day $t, \frac{T_t}{Q_t} = \frac{\bar{T}}{\bar{Q}}$, with the constraint that $T_t \leq 24$.

Therefore:

$$T_t = \begin{cases} \frac{Q_t \bar{T}}{\bar{Q}}, & \text{if } \frac{Q_t \bar{T}}{\bar{Q}} \leq 24 \\ 24, & \text{if } \frac{Q_t \bar{T}}{\bar{Q}} > 24 \end{cases}$$

The variable $QT_t$ is obtained in the following way:

For a given plant $i$, the following parameters are defined:

- $\alpha$: Minimum volume of stored water required to run the turbines (in m$^3$).
- $QT_{\max}$: Maximum turbine capacity in the plant (in m$^3$/s).
- $V_{\max}$: Maximum storage capacity of the reservoir (in m$^3$).

Let $(V_0)_t$ be the initial volume of water stored in the plant (in m$^3$), at the beginning of day *t*.

- If $(V_0)_t < \alpha \Rightarrow QT_t = 0$
- If $(V_0)_t \geq \alpha$, then:

If $(V_0)_t + 86400 Q_t \geq 3600 T_t QT_{\max} \Leftrightarrow \frac{(V_0)_t}{3600 T_t} + \frac{86400 Q_t}{3600 T_t} \geq QT_{\max}$, $QT_t = QT_{\max}$

If $(V_0)_t + 86400 Q_t < 3600 T_t QT_{\max} \Leftrightarrow \frac{(V_0)_t}{3600 T_t} + \frac{86400 Q_t}{3600 T_t} < QT_{\max}$, $QT_t = \frac{(V_0)_t}{3600 T_t} + \frac{86400 Q_t}{3600 T_t}$

The initial volume of water stored in the plant (in m$^3$) at the beginning of each day must be updated, as follows:

Let's define $QD_t$ the amount of spilled flow (in m$^3$/s):

- If $(V_0)_t + 86400 Q_t - 3600 T_t QT_t \leq V_{\max}$, then $QD_t = 0$.
- If $(V_0)_t + 86400 Q_t - 3600 T_t QT_t > V_{\max}$, there is spilling. The volume of spilled flow (in m$^3$) in day *t* is:

$$(VD)_t = (V_0)_t + 86400 Q_t - 3600 T_t QT_t - V_{\max},$$

Therefore the volume for the following day can be calculated using the following equation:

$$(V_0)_{t+1} = (V_0)_t + 86400Q_t - (VD)_t - 3600T_t\,QT_t.$$

## *2.3. Historical Reconstruction*

The Hydroclim model has been used to reproduce the operations of each of the three plants. Each of them has specific characteristics that requires a distinctive treatment. Logically, it is more difficult to reproduce the operations of plants with a greater operational capacity, as the managers of these plants have the ability to store water and process it at the most economically opportune time, as well as to adjust usage based on expected shortages.

The case of Mengíbar, the run-of-river plant, is much simpler due to its smaller operational capacity. It does not have a reservoir in and of itself, and the biggest challenge is to determine on a daily basis how much water may be processed, and when it should be spilled. The model provides a 97% correlation between historical production and reconstructed production since 1975 (Figure 3), which is when the plant was renovated and took on its current configuration.

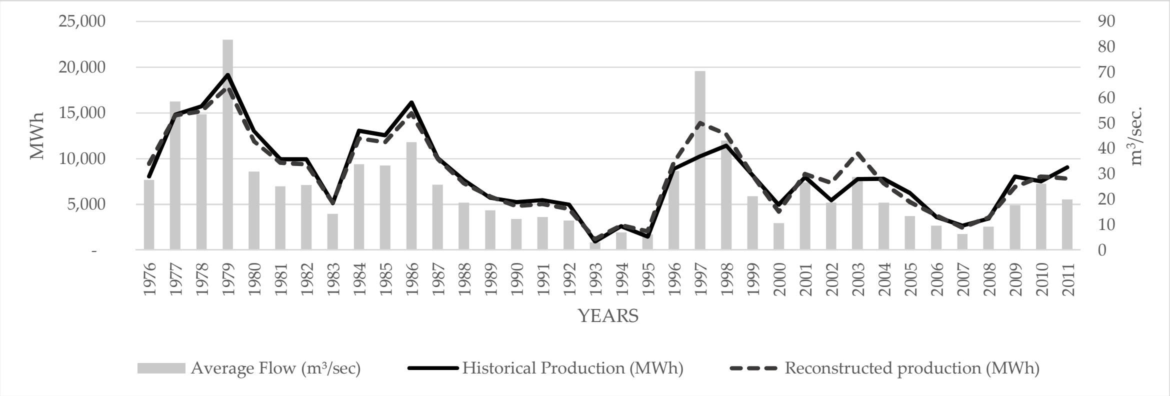

**Figure 3.** Historical production and reconstruction at the Mengíbar plant. Source: Own elaboration and ENDESA.

The modelling of the Cala plant faces the challenge of managing a certain storage limit, along with the need to spill in the case that this limit is exceeded. The correlation obtained in this case, for the period of 1961 to 2012, is 87% (Figure 4), with no correction for historical anomalies or periods of renovation (such as in 1976, when production ceased).

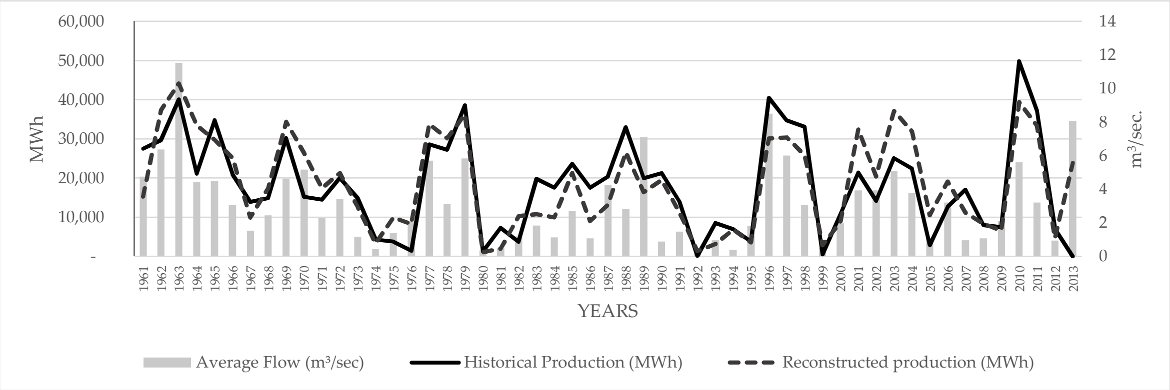

**Figure 4.** Historical production and reconstruction at the Cala plant. Source: Own elaboration and ENDESA.

The remaining plant, Tranco de Beas, is the most complex due to its large reservoir (in fact, it is considered limitless in the model). Therefore, the operational capacity of the plant operator is much greater. In this case, it has been difficult to account for decisions to halt production during certain times of year, despite having an available supply and flow. This anomaly has been solved by including an additional restriction on the plant operator, requiring that production be cut if minimum reserves for the following year were not met at the end of the irrigation season. This is the $\alpha$ parameter that was mentioned above. The correlation from 1966 to 2012 is 83% (Figure 5).

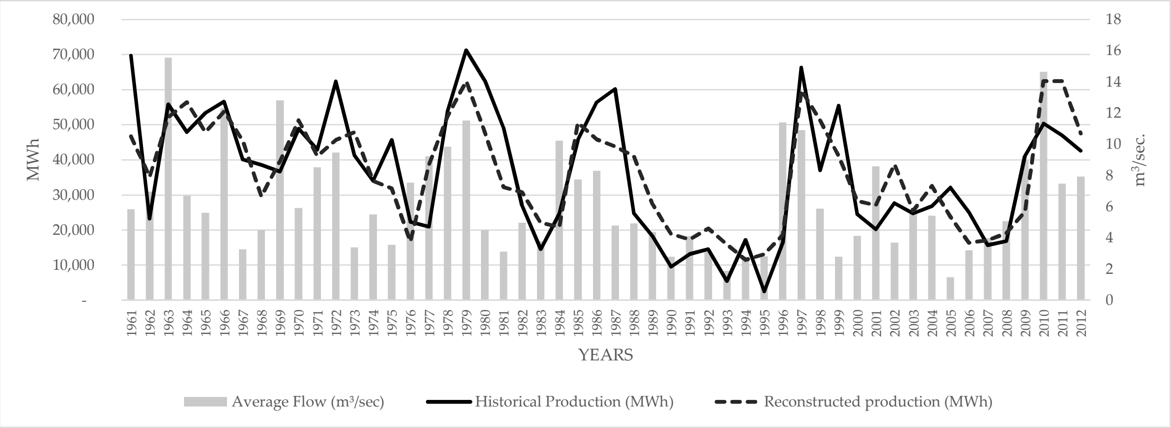

**Figure 5.** Historical production and reconstruction at the Tranco de Beas plant. Source: Own elaboration and ENDESA.

## 3. Production Projections

### 3.1. Hypothesis for the Projections

Once the model has been tested and calibrated to provide an acceptable correlation with historical data, the next step is to use it as the basis from which to project the potential impacts of climate change.

Climate change scenarios have been primarily based on work done by the Center for Studies and Experimentation of Public Works (CEDEX) under the Ministry of Public Works. CEDEX carried out a series of studies between 2010 and 2012 aimed at assessing the impacts of climate change on water resources and bodies of water. One of these reports [18] centers on production systems, using the hydrological model SIMPA to assess changes in available water resources in the main Spanish rivers in the A2 and B2 scenarios of the Fourth Assessment Report (4AR) of the Intergovernmental Panel on Climate Change (IPCC). These studies have already been used as a reference to evaluate changes in the Spanish energy system due to climate change [19].

The report contains projections of resource availability for the periods 2011–2040, 2041–2070, and 2071–2100, in relation to the reference period 1961–1990. In this case, the average change in runoff for the six models studied for the Guadalquivir has been used under the assumption of uniform demand (Table 2). All models point towards a reduction in runoff, ranging from −37 to −62% (A2) and from −5 to −44% (B2) in the long term (2071–2100).

**Table 2.** Variation of available resource (runoff) based on CEDEX average projections for the Guadalquivir, compared with 1961–1990. Scenarios A2 and B2. Source: CEDEX, 2012.

| Scenario | 2011–2040 | 2041–2070 | 2071–2100 |
|---|---|---|---|
| A2 | −19% | −32% | −46% |
| B2 | −29% | −20% | −26% |

The results of the CEDEX study represent an aggregate sum of the whole basin, with no differentiation between its different parts. In the projections, for lack of better information, it has been assumed that reductions in availability are equally applicable to all plants, although they are located in different sections and their individual contributions depend on distinct sources. That is, the reductions in water resources provided by CEDEX for the different periods have been transferred to the daily flow data available for the plants from 1961 to 1990. Therefore, the seasonal distribution of flow has been kept as in the original record.

In contrast with this source of information, two additional references have been used. Firstly, historical information for each plant provided by the company has been used to confirm the consistency of the projections. Secondly, rainfall projections for each region, provided by the Andalusian Government, have been used for scenarios A2 and B1 of the 4AR of the IPCC [20].

The selected approach might underestimate climate change impacts for two reasons. On the one hand, due to the limitations of the model, these projections do not take into account the impact of changes to the contributions needed to maintain a minimal ecological flow, or to meet certain guarantee curves for other uses, and subsequently the potential impact of this on energy production. That is to say, it has been assumed that spilled flow will be managed under the same assumptions as during the historical period. On the other hand, due to lack of information, the impact of periods of intense rainfall have not been considered, although seasonal variations may affect the performance of the plant [21].

### 3.2. Results

The results of these projections show a significant decline in production, which is consistent with the decrease in contributions projected by CEDEX. Except in Tranco de Beas, the reduction in production is always inferior to the decrease in runoff. On the other hand, and consistent with the CEDEX projections, the A2 scenario shows a growing reduction in contributions. However, the B2 scenario, which begins with greater reductions than A2, then shows an inverted U-shape, with the best results in the period from 2040–2071. Contributions then fall again, but more slowly than in the first period.

The following Figure 6–8 show the evolution of production at each plant for the A2 scenario, along with the moving average over the last 10 years and the linear trend.

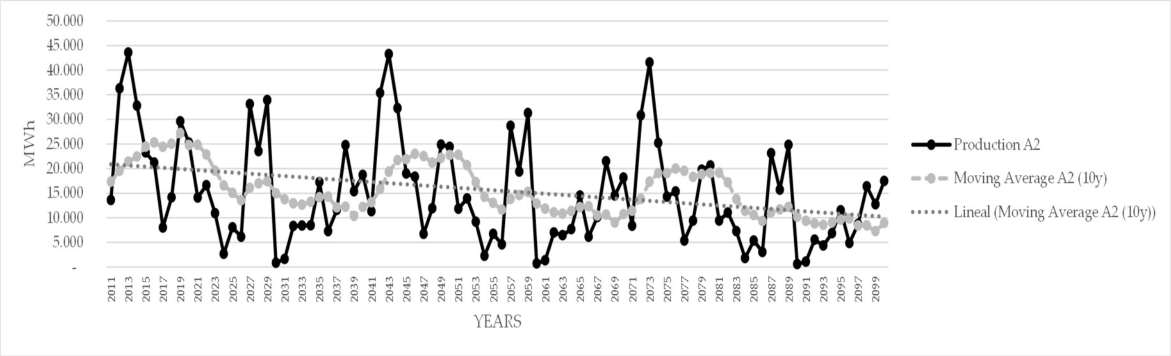

**Figure 6.** Projected production for Cala in MWh (A2).

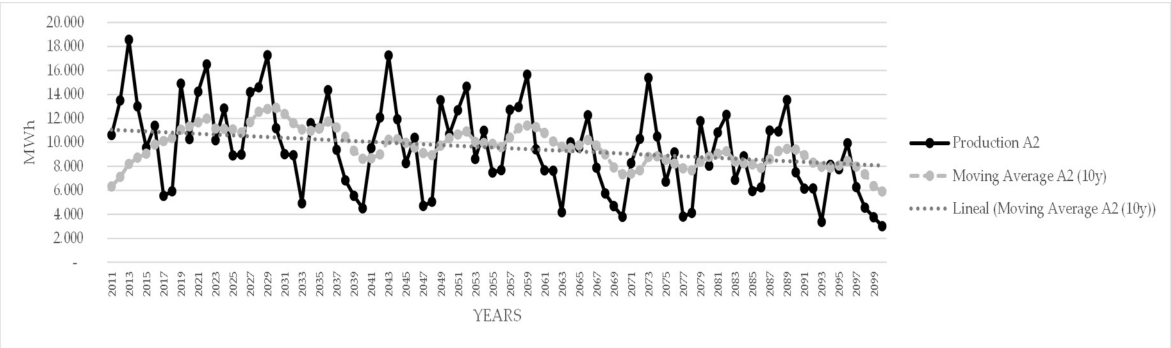

**Figure 7.** Projected production at Mengibar in MWh (A2).

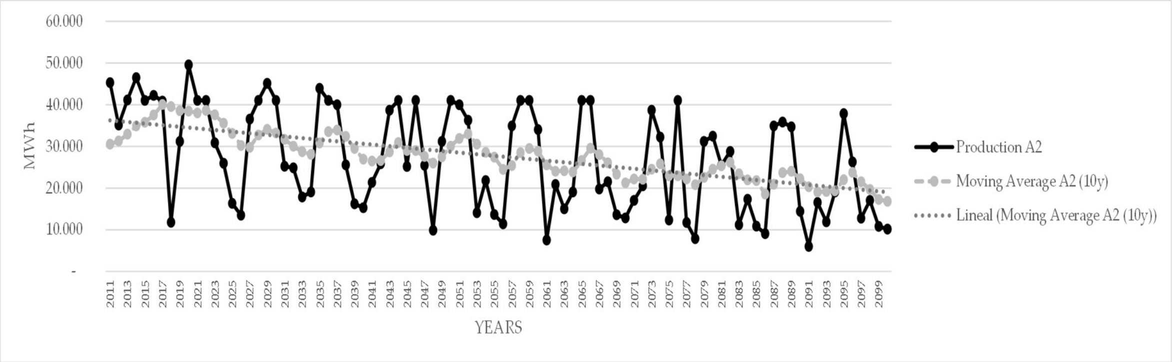

**Figure 8.** Projected production for Tranco in MWh (A2).

Figure 9 below offers a comparison of the changes in production from 1961–1990, along with the evolution of water availability reduction from CEDEX. As shown, the decrease in production is present in all scenarios and plants. By the end of the century this figure reaches a very noteworthy level, ranging between 30 and 49% for scenario A2 and 10 to 31% for scenario B2.

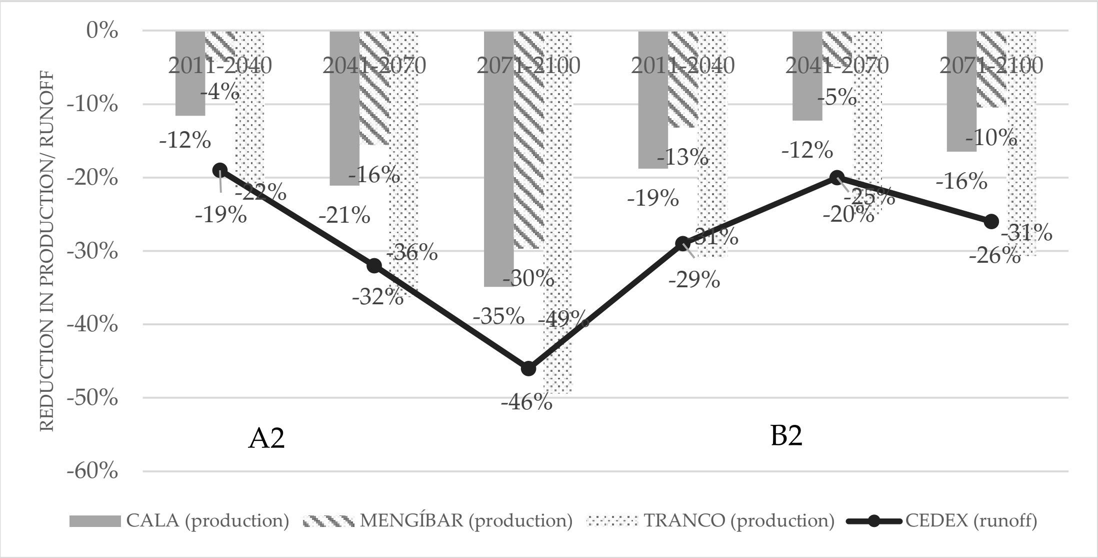

**Figure 9.** Comparison of projections and climate trends. Source: Own elaboration and CEDEX (2012).

As shown above, the decrease in production is higher in plants with greater storage capacity. The plants that, in their current configuration, least efficiently utilize water and are forced to spill excess flow are the least affected. Part of the decrease in flow simply implies that there is less spilling, given that that plant could not exploit even the received flow in the initial period. However, where storage capacity is greater, the implications are more significant because the decrease affects water that was in fact being utilized. For this reason, production decreases are most notable in Tranco de Beas, followed by Cala, and finally by the run-of-river plant in Mengíbar.

This effect is also linked to the fact that Tranco de Beas, like many other storage plants, needs to have a high installed capacity factor to be able to produce enough power in certain periods of time. Table 3 displays the production/installed capacity ratio for the plants in the past and in the future, for the A2 scenario. The plant in Mengibar shows the best ratio, followed by Cala, then by Tranco de Beas. This fact will be relevant for the economic analysis as well.

**Table 3.** Historical and projected production to power ratio (average annual production (MWh)/capacity (installed MW)). Source: Own elaboration based on data from ENDESA.

| Plant | Baseline | Projection (A2) | | | Projection (B2) | | |
|---|---|---|---|---|---|---|---|
| | **1961–1990** | **2011–2040** | **2041–2070** | **2071–2100** | **2011–2040** | **2041–2070** | **2071–2100** |
| Cala | 1530 | 1353 | 1207 | 996 | 1243 | 1343 | 1278 |
| Mengibar | 2723 | 2608 | 2299 | 1915 | 2364 | 2588 | 2438 |
| Tranco de Beas | 1054 | 826 | 671 | 533 | 728 | 789 | 730 |

### *3.3. Historical Background*

A relevant question for plant operators is, to what extent these data are consistent with the historical evolution of the plants, and their pertinence in the context of other studies.

With regard to the historical significance, as shown in the graphs below, the three plants already show a trend towards an important reduction in flow and production (the production for Mengíbar has been reconstructed with the current configuration for the years prior to 1975, given that only since then has the plant had this specific configuration). The first is more significant conceptually, as the second may stem from technical reasons or design changes. Despite some logical data dispersion, the consistent decrease can be observed in Figure 10 for Cala as the dotted line showing the linear tendency in flow evolution. The reduction in flow, according to the linear tendency, is substantial between 1961 and 2012 (44% in Cala, 82% in Mengibar and 28% in Tranco). This fact is influenced by the rainy start of the 1960's. However, tracing back to 1930 for the plants where information is available, we find reductions as well (33% in Cala and 73% in Mengibar).

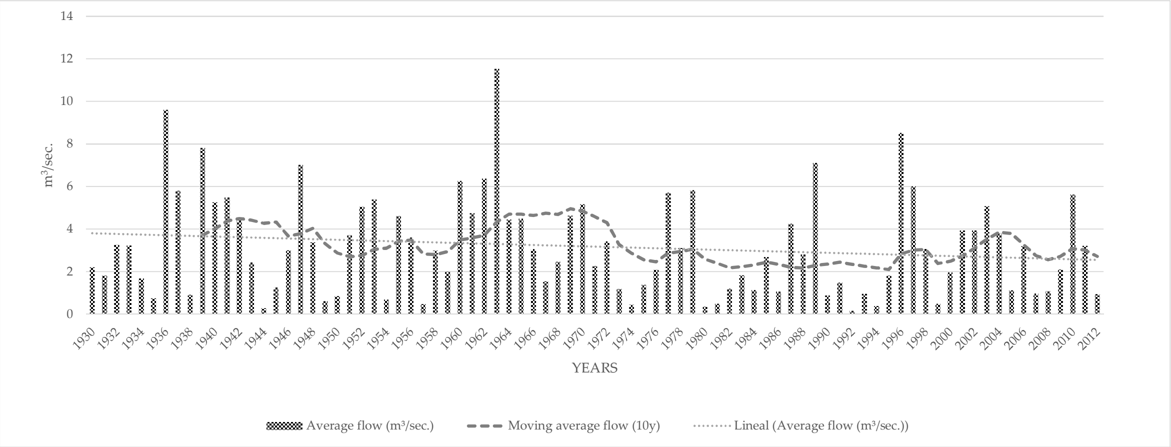

**Figure 10.** Historical evolution of flow at the Cala center. Source. Own elaboration based on data from ENDESA.

Subsequently, the historical trend of reduced flow was extrapolated for the period of the projections and compared to the flow hypotheses that were obtained by applying the CEDEX scenarios (A2). As can be seen in Figure 11, in the case of Cala the projection results and historical trends show relevant consistency. In the case of Mengíbar and Tranco de Beas (Figure 12 and Figure 13) the historical trend in flow reduction is much greater than that shown in the projections. In fact, following this trend, flow would reach zero in these plants before the end of the century.

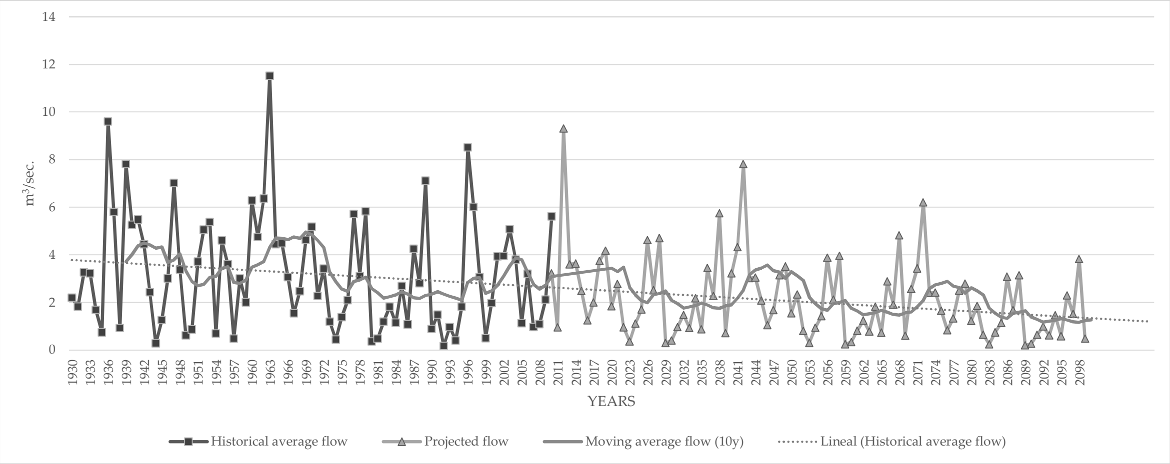

**Figure 11.** Historical and projected flow (m³/s), Cala center. Source: Own elaboration and ENDESA.

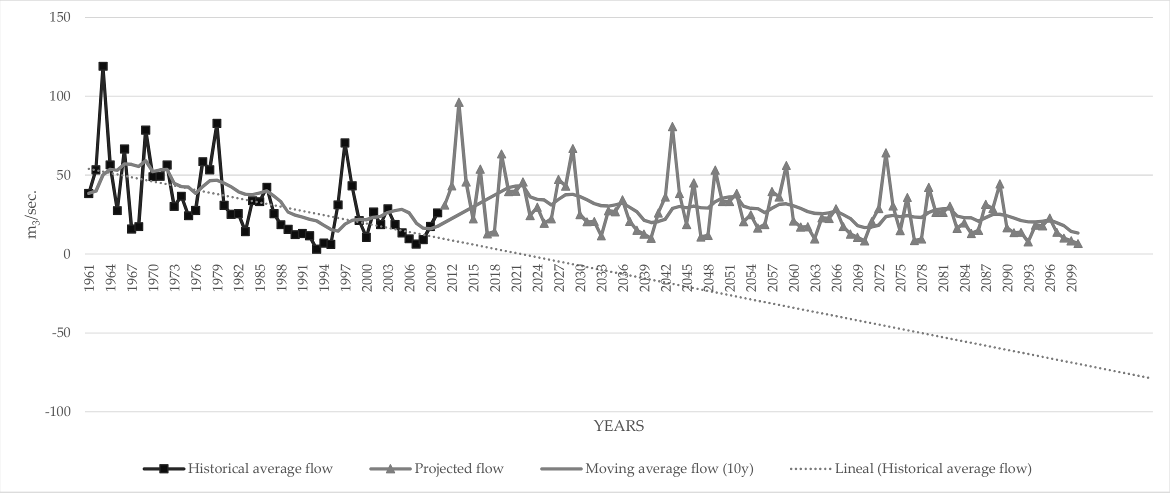

**Figure 12.** Historical and projected flow (m³/s), Mengibar center. Source: Own elaboration and ENDESA.

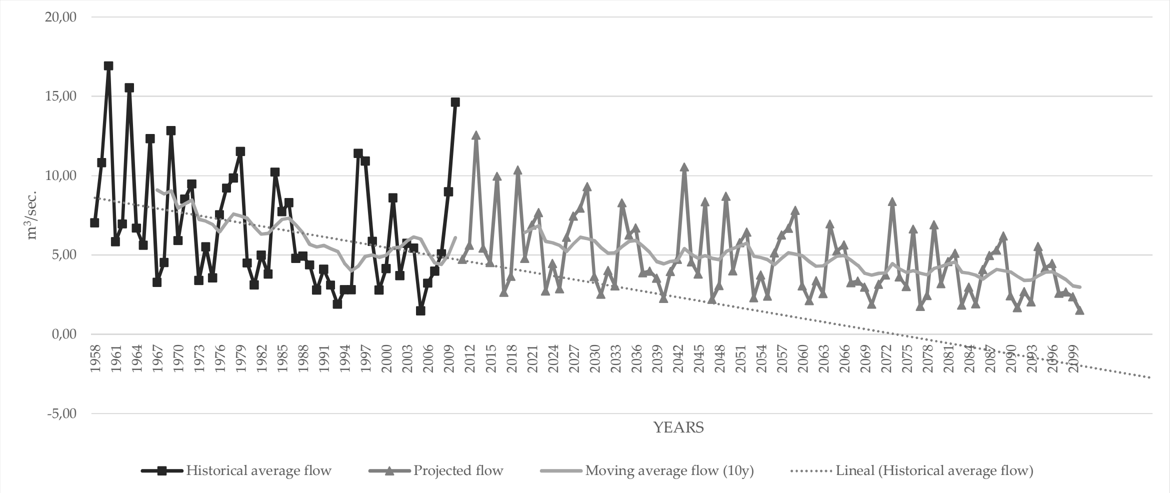

**Figure 13.** Historical and projected flow (m³/s), Tranco center. Source: Own elaboration and ENDESA.

### *3.4. Alternative Sources of Information*

There are only a few relevant sources with enough resolution to test these results. The results of the CEDEX projections that have been used above have been compared to those of the Regional Government of Andalusia. This government, as previously mentioned, conducted a study that offers data on rainfall reductions for each of the different Andalusian provinces for scenarios A2 and B1 of the 4AR of the IPCC [20]. Historical rainfall and flow data have been correlated, from a simple polynomial regression, to obtain flow data for each of the distinct rainfall scenarios. These data have been used in the model to project production until the end of the century.

Logically, this exercise implies greater uncertainty than the CEDEX projections, for various reasons. Firstly, because there are significant differences in rainfall within the provinces, and particularly because the contributions to each plant may be influenced by provinces located upstream.

Secondly, the historical correlation between flow and rainfall is relatively high in Cala and Tranco (83 and 85%, respectively), but much lower in Mengíbar (54%). In other words, considering existing historical information, rainfall can be an acceptable approximation to flow only in two plants. The relation between flow ($m^3/s$) and rainfall ($L/m^2$) in Tranco is represented in Figure 14.

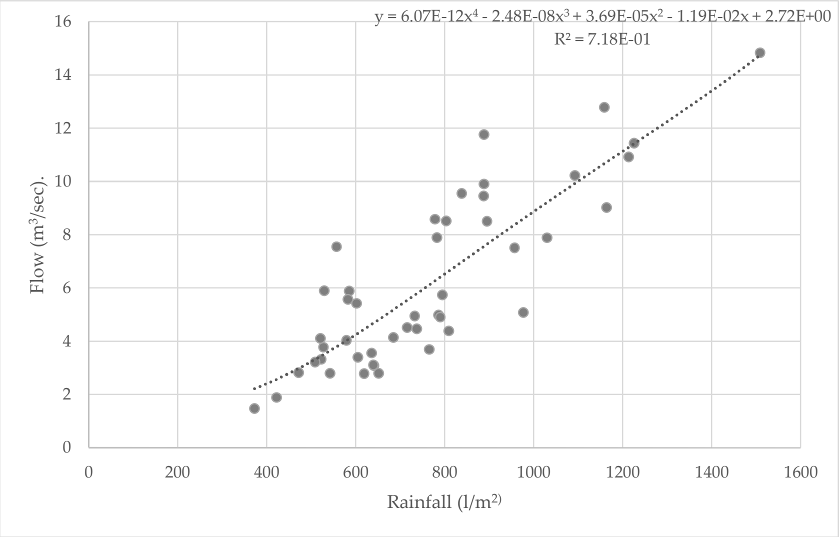

**Figure 14.** Flow and rainfall data (1967–2012), Tranco de Beas center. Source: Own elaboration based on data from ENDESA.

Below are the projections made using data from the Regional Government of Andalusia, compared with the results from CEDEX (Table 4). Generally, projected reductions obtained with the government data are more moderate than those from CEDEX, although the overall trend is the same. It should also be noted that the compared scenarios are within the same family, but are not exactly the same (A2 and B2 for CEDEX, and A2 and B1 for the Regional Government of Andalusia).

**Table 4.** Projected reductions in production (%). CEDEX vs. Regional Government of Andalusia.

| PLANT | PROJECTION | A2 | | | B2/B1 | | |
|---|---|---|---|---|---|---|---|
| | | 2011–2040 | 2041–2070 | 2071–2100 | 2011–2040 | 2041–2070 | 2071–2100 |
| Cala | CEDEX | −12% | −21% | −35% | −19% | −12% | −16% |
| | ANDALUSIA | −8% | −28% | −30% | −17% | −14% | −22% |
| Mengíbar | CEDEX | −4% | −16% | −30% | −13% | −5% | −10% |
| | ANDALUSIA | 0% | 0% | −1% | 0% | 0% | 0% |
| Tranco | CEDEX | −22% | −36% | −49% | −31% | −25% | −31% |
| | ANDALUSIA | −14% | −33% | −33% | −23% | −22% | −31% |

## 4. Economic Analysis

### *4.1. Hypothesis*

The company that runs these plants has not provided specific economic information for this analysis. Therefore, information is taken from literature and government standards developed along with the remuneration system for hydroelectric power plants in Spain under the so-called "Special Regime" (feed-in tariff). Although none of these plants operate under this special scheme, it has been assumed that their cost structure does not differ substantially from similar plants that operate under this regime.

As noted, the selected values remain constant over time, in accordance with the chosen *ceteris paribus* approach. Therefore, future changes have not been taken into account, such as changes in the electricity market, management upgrades, changes in the plants' configurations, new technologies, or other variables that could impact the cost and revenue structure.

Two types of economic analyses have been performed, one on operating margins and another on investments. In the first, the costs of civil works and engineering have been omitted, as these plants are in operation and the analysis only considers the investment required to replace machinery, as suggested by the company. This equipment is assigned a useful lifespan of 25 years, based on the regulatory lifespan set out by the Ministerial Order.

With regard to capital costs, a study conducted by the Boston Consulting Group for the Spanish Government has been used [22], along with the Ministerial Order 1045/2014. This study provides a detailed analysis by installed capacity and plant type, disaggregated by cost category (Table 5). A linear interpolation of values has been calculated, with total investment costs of 841 €/kW for Cala, 1572 for Mengíbar, and 759 for Tranco de Beas.

**Table 5.** Capital costs at hydropower plants. Source: Institute for Diversification and Saving of Energy (IDAE) (2011).

| | **Run-of-River Plants (1000 €/MW)** | | | | **Impoundment Facility (1000 €/MW)** | | | |
|---|---|---|---|---|---|---|---|---|
| Installed capacity (MW) | 1 | 10 | 25 | 50 | 1 | 10 | 25 | 50 |
| Industrial margin | 200 | 180 | 137 | 100 | 100 | 84 | 70 | 55 |
| Installation | 120 | 105 | 90 | 70 | 50 | 35 | 30 | 20 |
| Generator | 250 | 210 | 180 | 170 | 250 | 210 | 180 | 170 |
| Turbine | 250 | 210 | 200 | 200 | 250 | 210 | 200 | 200 |
| Other civil works | 200 | 180 | 150 | 120 | 150 | 140 | 130 | 120 |
| Headworks, canal and penstock | 600 | 600 | 600 | 600 | 175 | 175 | 175 | 175 |
| Total | 1620 | 1485 | 1357 | 1260 | 975 | 854 | 785 | 740 |

These estimates seem conservative in view of the literature, although the main sources do not offer such a detailed breakdown for Spain. On the other hand, existing studies show significant variations due to the fact that investments costs are, understandably, very different depending on the plant and location. IRENA estimates that 3/4 of investment costs are determined by the local physical characteristics, and gives values of 1000 to 8000 USD/kW for small power stations in the European Union [23]. More specifically, their curves depicting power and head show higher values than those of IDAE [22].

Meanwhile, while a study commissioned by the European Commission [24] do not offer a systematic classification of power, in categories equivalent to the analyzed plants it gives values of 1275–5025 €/kW, 975–1600 for medium sized plants, and 1450–5750 for the largest plants. The values do not greatly differ from those of IDAE, except in the case of Tranco de Beas, where they are substantially higher as, surprisingly, no economies of scale are reported for large plants.

Finally, a paper also commissioned by the Spanish Government [25] distinguishes between three types of plants, which can be linked to those mentioned here (run-of-river to 10 MW, storage plants of less than 10 MW, and storage plants of between 10 and 50 MW). Investment costs fluctuate between 2000, 1400, and 1100 €/kW, greater than those of IDAE [22].

For the estimation of operation and maintenance costs, IDAE [22] has been chosen in line with Order 1045/2014, which includes a separate analysis per plant type, size, and commissioning date. In this regard, costs are fixed per unit of power (between 40–50 €/MW, according to IDAE and are then adjusted for each plant so that historical costs per MWh produced resemble as closely as possible the estimates of Ministerial Order 1045/2014.

In the case of Tranco, corrections have been made, as the plant is operating well below capacity, and only two of the three groups are operating stably. It has therefore been estimated that operation and maintenance costs are 2/3 of what would correspond to the plant's theoretical installed capacity.

These data are consistent with the literature, despite the fact that there are very different reference values, given the large disparity in costs for hydroelectric plants depending on the type, size, and location. Furthermore, many of the pertinent papers have a different scope and consider different cost categories.

IRENA [23], for example, estimates a similar range of costs, of 45 to 53 USD/kW/year. De Jager et al. [24] give lower values for Europe, of 35 €/kW for the largest plants, and 40 €/kW for the smaller ones.

Several taxes have been considered in the assessment. The tax on electricity production has been taken into account, introduced by Law 15/2012, which records production and incorporation into the Spanish Electricity System (at a rate of 7% of the total revenues obtained by the taxpayer). Also considered is the currently applicable charge for the use of inland water for energy production (2.2% in plants of less than 50 MW, owing to article 8 of Royal Decree 198/2015). Finally, a charge of the Water Confederation, estimated at 3% (the value is not published in the concession), is added.

Of lesser importance, local taxes such as those on economic activities and property have not been taken into account. The Special Tax on electricity has not been considered, given that in its current form it taxes energy supply for consumption, rather than production. Finally, the Added Value tax is not included, due to its neutral impact on businesses.

Regarding revenue, Order 1045/2014 assumes an average market price of 52 €/MWh from 2017 which has served as the primary reference. However, some hydroelectric power plants, due to their operational capacity can choose the time to produce considering existing prices in the electricity market. To take this into consideration, an alignment ratio has been calculated to reflect the difference between the average daily electricity market price since 2011, and the weighted average that hydroelectric energy has been sold at (Table 6). This ratio is estimated at 6.672%, and has been applied to all of the analyzed centers, as it has been calculated with data from all existing hydroelectric power stations.

**Table 6.** Alignment ratio for hydroelectric power stations. Own elaboration based on data from The Spanish Electricity System.

| Year | Hydroelectric Weighted Average (€/MWh) | Daily Average Electricity Market (€/MWh) | Average Deviation |
|---|---|---|---|
| 2011 | 52.2 | 49.9 | 4.9% |
| 2012 | 50.6 | 47.2 | 7.9% |
| 2013 | 47.2 | 44.3 | 8.1% |
| 2014 | 44.8 | 42.1 | 7.3% |
| 2015 | 52.8 | 50.3 | 5.1% |

By reason of the *ceteris paribus* approach explained above, these costs and revenues remain stable over time. It has also been assumed that concessions do not change over time, as any change in the company managing concessions is not relevant to the objectives of this study. Similarly, no costs related to the hypothetical end of operating life of the plants have been considered.

### *4.2. Analysis of Operating Margin*

With these presuppositions in mind, results concerning the plants' margins are shown below. The period from 1961–1990, on which CEDEX projections are based, is considered a Business As Usual scenario, and has been compared with the results for all plants for each distinct scenario.

As shown in the historical period, in accordance with the above-mentioned hypotheses, Mengíbar is the center with the highest operating profit. This is because it is the center with the best ratio of production to installed power capacity, and operating and maintenance costs have been estimated as fixed. Tranco de Beas shows the worst results, as it needs a higher capacity factor per unit of electricity produced, when valued in light of its historical performance.

Concerning future evolution, in the A2 scenario the two plants with a reservoir, Cala and Tranco de Beas, end up being unprofitable. In the B2 scenario this only occurs with Tranco de Beas. Mengíbar is, once again, the least affected plant as the projections show a small drop in production and because it is, historically, the plant with better operating margins. The results are shown in Table 7.

**Table 7.** Evolution of operating margins at pilot centers.

| **Plant** | **Operating Margins** | | |
|---|---|---|---|
| | **1961–1990** | **PROJECTED (2011–2100)** | |
| | | **A2** | **B2** |
| *Cala* | 17% | −6% | 2% |
| *Mengíbar* | 42% | 32% | 37% |
| *Tranco* | 15% | −27% | −16% |

If the analysis is disaggregated by periods of time, (as shown in Table 8) in scenario A2, Cala would cease to have a positive margin for the period of 2041–2070, and Tranco the Beas even from 2011–2040. In the B2 scenario, Cala would continue to be profitable while Tranco would be unprofitable again from the first period (2011–2040).

**Table 8.** Evolution of operating margins (%) over time.

| **Plant** | **BaU** | **A2** | | | **BaU** | **B2** | | |
|---|---|---|---|---|---|---|---|---|
| | **1961–1990** | **2011–2040** | **2041–2070** | **2071–2100** | **1961–1990** | **2011–2040** | **2041–2070** | **2071–2100** |
| *Cala* | 17% | 7% | −3% | −22% | 17% | 0% | 7% | 2% |
| *Mengíbar* | 42% | 38% | 33% | 22% | 42% | 33% | 39% | 36% |
| *Tranco* | 15% | −5% | −27% | −56% | 15% | −18% | −10% | −17% |

### *4.3. Investment Analysis*

Lastly, an analysis has been carried out regarding a hypothetical investment from scratch. That is to say, to what extent a full investment to build the plants in their current configuration would be profitable at each of the plants, considering the expected decrease in electricity production. In this case therefore, the full set of capital cost categories has been considered, including civil works and engineering. The period of the investment analysis is fifty years, beginning in 2011, the first year projected.

A discount rate of 2% has been used, consistent with other studies in the sector in Spain [26]. Two financing options have been analyzed. In the first, funding is considered to be purely internal, and no opportunity cost is applied. In the second, following the same sources, there is external funding of 80% of capital, at an interest rate of 6%, under an equated yearly installment (equal payments during the loan life cycle to pay off interests and capital).

Table 9 shows the current net values for the different plants, considering A2 and B2 scenarios. Consistent with the results of the profitability analysis, only the Mengíbar plant shows positive values for such an investment, and just for the 100% internal financing assumption.

**Table 9.** Net present values of investments in pilot centers, A2 and B2 scenarios.

| Plant | A2 | | B2 | |
|---|---|---|---|---|
| | **100% Internal** | **80% External** | **100% Internal** | **80% External** |
| *Cala* | −1,832,872 | −10,391,233 | −2,425,443 | −10,983,804 |
| *Mengíbar* | 3,366,106 | −1,882,264 | 2,901,465 | −2,346,905 |
| *Tranco* | −16,533,271 | −40,526,083 | −18,482,928 | −42,475,740 |

## 5. Discussion

This article has analyzed to what extent decreases in average rainfall due to climate change could affect the margins and operations of hydroelectric power plants in the long term. As a result, in the absence of adaptive measures, a decrease in the plants' productivity is to be expected, which will significantly impact their margin, except in the case of the run-of-river plant at Mengíbar.

With regards to the physical approach, the primary reference has been public projections on the availability of water resources. The main uncertainty stems from projections on contributions. In this sense, it will be important to improve upon and update these projections over time, as new information becomes available.

A common limitation in the projections of CEDEX and of the Andalusian Government is that they are based on scenarios from the 4AR of the IPCC. Future analysis would benefit from more geographically precise projections, based on the Fifth Assessment Report (5AR) of the IPCC. In the case of CEDEX, it is important to note that the utilized models, when applied to the historical data, show results that are lower than the actual contributions. This is the best reference to date for the impact of climate change on water resources in Spain, but remains a work in progress and could be improved upon.

Additionally, the potential impact that current or future guarantee curves may have on the management of the plant has not been taken into account. Incorporating this could further reduce the expected production. Interaction of users in water scarcity scenarios is becoming very relevant in recent literature [27,28].

One of the most relevant methodological decisions was the *ceteris paribus* approach. As explained above, the reason was to avoid distortions due to other factors in the results, especially considering the long-term framework of the assessment. However, it is to be expected that the electricity production sector will change substantially over time taking into account, for instance, the growing share of renewable energies in the electricity mix, which may require a bigger involvement from storage plants for regulation. The conclusions of this paper could benefit from other studies that shed light on the future evolution of the sector.

From an economic standpoint, the main uncertainty is that associated with the evolution of the electricity market in Spain, which is outside the scope of this article. What is more, this study has operated under the assumptions of the government's economic model, which do not necessarily coincide with real costs and benefits.

## 6. Conclusions

The study has shown that the reduction in availability of water resources linked to climate change may pose a significant risk for hydroelectric production in southern Spain. Three hydroelectric power plants have been studied. In all of them the expected reduction in runoff will significantly affect the production of the plants. Depending on the scenario, reductions in production by the end of the century range between 30% and 49% (A2) and between 10% and 31% (B2). This trend is not, nevertheless, inconsistent with historical data, which already show a significant decrease in flow at the plants.

The reduction in production, according to our economic and financial hypothesis, will substantially affect the operating margins of the plants. Under the A2 scenario, two of the plants would even cease to have positive margins. Under the B2 scenario one of them would be in this situation. This reduction in water resources would potentially affect new investments in the sector as our model shows only positive values in one of the plants in a hypothetical investment from scratch.

The run-of-river plant of Mengibar performs better under these scenarios whereas Tranco de Beas, the plant with higher storage capacity, is the most affected. However, the authors believe this is not so much related to having a reservoir or not, but rather to the ratio between production and installed capacity, according to our assumptions. In this regard, the plants with more operational capacity may have an additional advantage on the market price, which has not been considered here.

These conclusions will benefit from further improvements that can reduce the uncertainty of the analysis. More updated and accurate projections would help as well as a more detailed assessment that integrates the needs of the energy sector with needs of other sectors that will face a shortage as well.

In any case, the time horizon of the study is long-term and many changes are to be expected in the energy sector during that time. Generally, this allows for time to address potential adaptive measures, and to continue improving upon the informational groundwork of these projections.

Concerning public policy design, the logical conclusion of this paper is that climate change may have a decisive impact on the profitability of hydroelectric power plants, which represents an essential pillar in policies to mitigate climate change in Spain. Despite existing uncertainties, the magnitude of the expected changes suggests that this factor should be closely monitored by energy planners and decision makers in a context where climate change may impact as well other generation technologies [3,4]. The combination of our methodology with an assessment at country level based on a top-down methodology would shed more light on this matter, following recent research (such as [7] or [8]).

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# Impacts of Climate Change on Wind Energy Power – Four Wind Farms in Spain[1]

Abstract: There is a growing interest on how climate change may affect the energy sector, including changes in wind energy generation. This paper builds on existing research adding an economic component that considers how climate change can affect operating margins and investment values in specific wind farms in Spain. A projection of wind speed was carried out using an ensemble of three climate models, two scenarios (RCP 4.5 and 8.5) and two time periods (2018-2041 and 2042-2065) per plant. Using historical power curves, the changes in wind speed were converted to production output. The results show variations in production of up to 8% and changes in operating margins up to 10%. Seasonal generation may fluctuate as well, with an increase in summer and decrease in winter. An investment analysis was also conducted to consider how climate change may influence future developments in the sector.

Keywords: climate change; climate change adaptation; wind energy; energy economics.

## 1. Introduction

Renewable energies are increasingly important in the energy mix of many countries. In particular, global wind energy generation has grown by more than 20% per year over the last nine years [1]. Given that half of the world's wind power capacity has been added in just the last five years, and it is now the most important source of new power generating capacity in Europe and the United States [2], it is essential to understand which variables may impact its performance. It should also be highlighted that wind energy plays a very important role in climate change mitigation, which has become a priority for the international community [3].

Climate change itself poses a potential risk for wind electricity production, as a changing climate may alter atmospheric dynamics and affect wind patterns[4]. Therefore, it is more important than ever to evaluate the impacts of future climate change scenarios on wind speed and other variables that might affect wind production, as they are a potential high risk for investors [5]. Wind turbines are increasing not only in capacity, but size as well, making them even more vulnerable.

Wind speed is the most important driver of wind energy that can be affected by climate change [6], however there is less research on aspects such as extreme wind events and gusts, icing of the blades, sea ice, permafrost or air density. Changes in these elements depend on variables that are much more difficult to predict [7].

Over the last decade, a vast number of studies have been carried out to forecast long-term wind patterns in the context of climate change. Most of this studies have been focused on developed countries, especially in the US [5,8–11]. In the last years, a few developing countries have been taken into consideration as well [12–16]. Most of these studies project a decrease in wind speed in the future [4]. However, most of the studies suggest that it is unlikely that mean wind speeds and energy density will change more than the inter-annual variability [7].

With respect to Europe, most studies project an increase in wind speed in the north and a decrease in the south, specifically in the Mediterranean, however these variations do not exceed

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magnitudes of 10-20% [17–22]. These predicted changes are usually more intense in scenarios with a higher concentration of greenhouse gases in the atmosphere [6,17,22].

Therefore, the Mediterranean region usually faces the biggest changes, and Spain and Portugal are the countries whose energy system will be most severely affected by climate change, all technologies considered [23]. Regarding wind power output in Spain, a long-term assessment throughout the 20th century showed a decrease in Central Spain, versus an increase in the Gibraltar Strait area [24]. When it comes to future projections, one study analyzed changes in mean wind speed in eleven representative clusters across Spain, forecasting moderate reductions for all, but never greater than 3% [25]. Another more detailed assessment, including seasonal variations, also projected a reduction in wind power, with the exception of some areas in Southern Andalusia and the Gibraltar Strait region [26]. The general decreasing trend is consistent with projections for offshore wind with an expected reduction of less than 5% in most areas [27].

There is a lack of studies that provide an economic assessment on the consequences of these changes, even if some papers project impacts on electricity prices [28,29]. This gap can also be found in other renewable sources of generation [30,31].

The goal of this paper is twofold. On the one hand, an analysis was conducted to determine whether expected changes in wind speed may substantially affect electricity production at selected wind farms in Spain. On the other hand, an economic assessment has focused on how this would affect operating margins and investments in the sector, particularly in the context of a new regulatory regime in Spain that is reducing public subsidies on renewable energies. The study looked at four wind farms in Spain owned and operated by the company Acciona.

Accordingly, the paper is structured as follows: section 2 gives an overview of the methodology, including a description of the plants and any economic assumptions. Section 3 summarizes the results of the projection in terms of wind speed, production and seasonality. Section 4 analyzes the economic impact on operating margins and investment parameters. Sections 5 focuses on the discussion of the methodology and results. Finally, the paper closes with some concluding remarks.

## 2. Methodology

### 2.1. Description of the plants

As previously noted, this paper analyzes the impact of climate change on four wind farms. The farms were chosen among more than 200 that are currently managed by the company Acciona, due to their operating and technical features. The final goal is to apply the conclusions made here to other plants. Table 1 summarizes the most important characteristics of the plants.

**Table 1.** Characteristics of the analyzed plants. Source: ACCIONA.

| Wind farm | Region | Beginning of operations by Acciona | Total power (MW) | Turbines (number) | Power (average kW per turbine) | Turbine type |
|---|---|---|---|---|---|---|
| *AEGA (Cuadramón)* | Galicia | 1999 | 18.75 | 25 | 750 | Neg Micon NM44/750 |
| *El Perdón* | Navarre | 1994 (renovated and expanded in 1995 and 1996) | 20 | 40 | 500 | Gamesa G42/600, V42 and V39 (500) |
| *Río Almodóvar* | Andalusia | 2009 (previously since 2004) | 12.8 | 16 | 800 | MADE AE 56 |
| *Rubió* | Catalonia | 2005 | 49.5 | 33 | 1500 | Acciona AW 1500/77 |

Location was a very important variable in the selection as well. The wind farms are located far from each other (as shown in Figure 1) and in representative areas that allow for some comparison with existing literature on wind resources in Spain [25,26]. Therefore, the sensitivity of the plants can be tested against other relevant sources of information.

**Figure 1.** Location of the wind farms. Source: own elaboration.

Establishing an extended historical record for projecting wind speed is usually a challenge, as most wind farms have not been in operation for long periods of time [24,32]. In this case, Acciona provided hourly information on wind speed, temperature and active power for each of the plants for the period 2010-2016[2] (reference period). As the information was generated by several metering devices, with some gaps, 1.8 % of historical registers were corrected. Additionally, a reanalysis of wind speed was conducted by Acciona, extending historical records back to 1987 with simulated data, as will be explained in section 3.2.

### *2.2. Methodological outline for the projections*

Projections of surface wind speed depend critically on the assessment methods used. In fact, these projections may very well be more dependent on methodology than other climate variables, such as temperature or pressure [5]. Changes in wind production do not depend only on changes in wind velocity, but also on wind shear or wind velocity distributions [14]. However, climate models do not provide information for these other factors and, therefore, wind speed is the only changing variable in the probability density function considered in this paper.

Wind power is very sensitive to any change in wind speed, as the wind power flux is proportional to the cube of the speed [4–7] among others).

$$\boldsymbol{Pflux = 1/2 \cdot \rho \cdot U^3}$$

where Pflux is the wind power flux (or wind energy density), U is the wind speed and ρ is the air density.

The methodology used in this paper to project production can be summarized in five steps.

A) Ex post power curves.

To model the sensitivity of production to wind speed several alternative methods were considered: econometric methodologies (linear and polynomial regressions) and technical methods

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[2] Except for Rio Almodóvar, where active power was only available after 2011.

(manufacturer power curves and ex post power curves). Ex post curves were built by calculating the average hourly active power for each wind speed during the seven years of the reference period (using bins with a 0.5 m/sec resolution). The ex post curves showed a better correlation with historial data than any other method across all wind farms (95% in Río Almodóvar, 93% in Cuadramón and Rubió and 87% in El Perdón) as well as limited differences in absolute figures (always less than +/- 0.6%).

For a given farm, consider the following hourly data provided by Acciona:
$(x_i, y_i)$, for $i = 1, 2, ..., I$,
where $x_i$ is the wind speed (in m/sec) and $y_i$ is the active power (in MW) at time $i$.
Let $[0, v_{\max}]$ be the interval of possible values of the wind speed. In this interval a partition is defined in the following way:
$[0, 0.5), [0.5, 1), [1, 1.5), ..., [v_{k-1}, v_k), ..., [v_{K-2}, v_{K-1}), [v_{K-1}, v_K]$,
where $v_0 = 0, v_K = v_{\max}, v_K - v_{K-1} \leq 0.5$, and $v_k = v_{k-1} + 0.5$, for $k = 1, 2, ..., K-1$.
Consider then the bins $B_k$, where $B_k = [v_{k-1}, v_k)$, for $k = 1, 2, ..., K-1$, and $B_K = [v_{K-1}, v_K]$.
For each $(x_i, y_i)$, allocate $(x_i, y_i)$ to bin $B_k$, such that $x_i \in B_k$.
Define $\tilde{y}_i$ as the mean value of the quantities $y_r$ which belong to bin $B_k$.
The ex post curve is constructed from $(x_i, \tilde{y}_i)$, for $i = 1, 2, ..., I$.
The correlation between $\{y_i\}_{i=1,...,I}$ and $\{\tilde{y}_i\}_{i=1,...,I}$ is calculated.

B) Projections.

The ex post curves were later used to ascertain production under future climate change scenarios. To do so, the results from EURO-CORDEX (regional climate model inter-comparison project [33], 11 global climate models) through the Copernicus tool, which provides wind speed data and projections at heights of 10 m for each wind farm until 2065 (12 km x 12 km resolution). Two Representative Concentration Pathways (RCP) developed for the 5th Assessment Report of the Intergovernmental Panel on Climate Change were used: RCP 4.5 and RCP 8.5 [34,35]. Despite the uncertainties of global climate models, they are the most well-trusted source for projections [16]. For each farm, an ensemble was established using an average of the three models that showed the best correlation with historical data, as it is explained next.

Consider the hourly data
$\{x_i\}$, for $i = 1, ..., I$,
corresponding to the wind speed at turbine hub height H.
Now, the grid in which the wind farm is located in the EURO-CORDEX initiative (with 11 global climate models) has to be obtained. For each of the 11 models, the wind speeds for year and season are taken form EURO-CORDEX:
For each model $M_l, l = 1, ..., 11$,
$\{v_j^l\}_{j=1,...,28}$
are the past wind speeds for years 2010 to 2016, given by the EURO-CORDEX initiative for the grid in which the wind farm is located, where j=1 corresponds to the season (December 2009, January and February 2010), j=2 to (March, April, May 2010), j=3 to (June, July, August 2010), j=4 to (September, October, November 2010), j=5 to (December 2010, January, February 2011), …, j=28 to (September, October, November 2016).

From the data $\{x_i\}_{i=1,\ldots,I}$ the values $\{x_j^m\}_{j=1,\ldots 28}$ are obtained where $x_j^m$ is the mean value of $x_i$ belonging to season $j \in \{1,\ldots,28\}$.

For each model $l \in \{1,\ldots,11\}$, the correlation between $\{v_j^l\}_{j=1,\ldots,28}$ and $\{x_j^m\}_{j=1,\ldots 28}$ is calculated.

The three global climate models for which such correlation is higher are selected.

Define $\{v_j\}_{j=1,\ldots,28}$, where $v_j$ is the mean value of the speeds $v_j^l$, among the three models which have been selected.

Using the EURO-CORDEX simulations, from the past wind speeds $\{v_j\}_{j=1,\ldots,28}$, the projections of wind speeds for the future $\{w_f\}_{f=1,\ldots,F}$ are obtained, where $f=1$ is the season DecJanFeb2018, $f=2$ is MarAprMay 2018, $f=3$ is JunJulAug 2018, $f=4$ is SepOctNov 2018, …, $f=F$ is SepOctNov 2065 (in fact, $F=192$), , for each of the two RCPs (4.5 and 8.5), where the average for the three selected models has been included in each of the values corresponding to the future.

C) Vertical extrapolation.

The speed data and projections provided by EURO-CORDEX are given for heights of 10 meters, therefore these data have to be transformed for heights of H meters, using the formula

$UH = US\left(\frac{H}{10}\right)^{\alpha}$, [17,24] among others, where *UH* is the wind speed at turbine height H, *US* is the wind speed at 10 meters and $\alpha$ is an ad-hoc parameter that denotes the contribution of the site roughness for the speed vertical gradient of the atmospheric boundary layer. The ad-hoc value of $\alpha$ is calculated as follows: take the values $\{x_j^m\}_{j=1,\ldots 28}$, at height H, and the values $\{v_j\}_{j=1,\ldots,28}$, at height 10, $\alpha$ is taken as the constant value in order that these two series are as close as possible.

D) Downscaling.

For the projection, a statistical downscaling was performed using the Delta Method [14,36], as explained next.

Consider the past wind speeds $\{v_j\}_{j=1,\ldots,28}$, corresponding to each of the seasons for years 2010 to 2016. For each season, the mean value is calculated in accordance with the following expressions:

$$v_s^m = \frac{1}{7}\sum_{r=0}^{6} v_{s+4r}, \quad \text{for } s = 1,2,3,4$$

where s=1 is the season DecJanFeb, s=2 corresponds to MarAprMay, s=3 is JunJulAug and s=4 is the season SepOctNov.

Therefore, the following mean values corresponding to each season in the past are obtained $\{v_s^m\}_{s=1,2,3,4}$.

On the other hand, for each of the two RCPs (4.5 and 8.5), the values corresponding to each future season are obtained from 2018 to 2065 $\{w_f\}_{f=1,\ldots,F}$.

Now the time series $\{v_s^m\}_{s=1,2,3,4}$ and $\{w_f\}_{f=1,\ldots,F}$ are compared in the following way:

Calculate the following differences, for $f = 1,...,F,$ :

$d_1 = w_1 - v_1^m$, $d_2 = w_2 - v_2^m$, $d_3 = w_3 - v_3^m$, $d_4 = w_4 - v_4^m$, $d_5 = w_5 - v_1^m$, $d_6 = w_6 - v_2^m$, $d_7 = w_7 - v_3^m$, $d_8 = w_1 - v_4^m$,...., that is:

$$d_f = \begin{cases} w_f - v_1^m, & \text{if} \quad f+3 \text{ is a multiple of } 4, \\ w_f - v_2^m, & \text{if} \quad f+2 \text{ is a multiple of } 4, \\ w_f - v_3^m, & \text{if} \quad f+1 \text{ is a multiple of } 4, \\ w_f - v_4^m, & \text{if} \quad f \text{ is a multiple of } 4. \end{cases}$$

The respective variations from the past to the future, expressed on a per unit basis are the following:

$$D_f = \begin{cases} d_f / v_1^m, & \text{if} \quad f+3 \text{ is a multiple of } 4, \\ d_f / v_2^m, & \text{if} \quad f+2 \text{ is a multiple of } 4, \\ d_f / v_3^m, & \text{if} \quad f+1 \text{ is a multiple of } 4, \\ d_f / v_4^m, & \text{if} \quad f \text{ is a multiple of } 4. \end{cases}$$

E) Representative year and production projection.

Rather than calculating the average wind speed per hour in the reference period, for each plant a representative year was established in terms of production and wind. This is to account for the non-linear relationship between wind speed and production in the first part of the power curve (where most registers are located), and therefore average wind does not represent average production.

Take the hourly data provided by Acciona

$(x_i, y_i)$, for $i = 1, 2, ..., I.$

Define the mean value of the active power corresponding to each of the years from 2010 to 2016, in the following way:

$$Y_1 = \sum_{i \in year\,2010} y_i, \quad Y_2 = \sum_{i \in year\,2011} y_i, \quad ... \quad , \quad Y_7 = \sum_{i \in year\,2016} y_i$$

Define the annual mean production corresponding to the years 2010 to 2016 as $\overline{Y} = \frac{1}{7}\sum_{n=1}^{7} Y_n$.

The year $n^*$ is chosen which solves the problem:

$\min_{n \in \{1,...,7\}} \left| Y_n - \overline{Y} \right| \Rightarrow n^*$ is the representative year.

Now, take all the hourly data corresponding to year $n^*$, $\left\{(x_i, y_i)\right\}_{i \in year\, n^*}$.

Now the values $x_i$ corresponding to year $n^*$ are slightly modified (multiplied by a constant), to solve for $\left| Y_{n^*} - \overline{Y} \right| = 0$, passing $x_i$ through the ex post curve satisfying the condition $\sum_i \tilde{y}_i = \overline{Y}$.

$\left\{\hat{x}_i\right\}_{i \in year\, n^*}$ are these (slightly) modified values, and their corresponding quantities in the ex post curves are $\tilde{\tilde{y}}_i$, with $\sum_i \tilde{\tilde{y}}_i = \overline{Y}$.

Therefore, the data $\left\{\left(\hat{x}_i, \tilde{\tilde{y}}_i\right)\right\}_{i \in year\, n^*}$. is obtained

The values $\hat{x}_i$, corresponding to the year $n^*$ are classified for each of the seasons $s = 1,2,3,4$ and for each season the mean value is obtained. Therefore, the following mean values corresponding to each season in the past are $\left\{X_s\right\}_{s=1,2,3,4}$.

For each of the two RCPs (4.5 and 8.5) the wind speed corresponding to each season of the future $\{XF_f\}_{f=1,\ldots,F}$ , is obtained using the differences previously gathered:

$$XF_f = \begin{cases} X_1(1+D_f), & \text{if} \quad f+3 \text{ is a multiple of } 4, \\ X_2(1+D_f), & \text{if} \quad f+2 \text{ is a multiple of } 4, \\ X_3(1+D_f), & \text{if} \quad f+1 \text{ is a multiple of } 4, \\ X_4(1+D_f), & \text{if} \quad f \text{ is a multiple of } 4. \end{cases}$$

The variations obtained from the climate models per year and season were later applied to each hourly register of the representative year, providing a wind projection for the years 2018 to 2065. This was then transformed into production using the above-mentioned ex post curves.

### *2.3. Methodological outline for the economic analysis*

Investment costs of onshore wind energy have dropped since the 1980s due to economies of scale. While the rated capacity of new turbines has increased, the unitary cost (labour and materials) has remained constant, or even decreased [37]. Despite a change in tendency between 2004 and 2010, mainly due to the higher cost of commodities, prices seem to have stabilized since then [38]. Operation and maintenance costs have decreased over time as well, both because of economies of scale and because newer turbines require less maintenance [39].

The analysis carried out for this paper was focused on operating margins. Official sources of information were used as the baseline scenario, both for income and costs. It allowed to test whether wind generation will be affected by climate change in the specific context of the current regulatory framework and incentives. However, cost parameters provided by Acciona for each of the wind farms were used as well and will be presented in a separate analysis.

Operating margins are calculated as follows:

$$OM = \frac{ES + IS - CAPEX - OPEX - T}{ES + IS}$$

where:

OM is the *operating margins* of each wind farm.

ES is *energy sales*, which considers the product of energy sold in the market and the *adjusted price* (AP) that will be explained below.

IS refers to the *Investment subsidy* that some plants can receive during their regulatory time span.

CAPEX is the *capital expenditure.*

OPEX is the *operating expenses.*

T refers to *taxes.*

When calculating ES, the chosen reference for the price of electricity is that set by the Spanish Government in Order 1045/2014, which assumes an average market price of 52 €/MWh from 2017 onwards. This reference was confirmed by Order ETU/130/2017. The price was adjusted as shown in the following equation:

$$AP = RP \cdot SD \cdot AR$$

where:

AP is the *adjusted price*.

RP is the above-mentioned *reference price* (52 €/MWh).

SD is the historical *seasonal deviation* from the *reference price*. This variable calculates the average deviation of prices in each month from the average price of each year. This variable will become relevant as the projections change the distribution of production throughout the year.

AR is the *alignment ratio*, which calculates how the weighted monthly average electricity price for wind in one month differs from the average price in the market for that month. Due to its lack of flexibility, wind electricity is on average sold at a lower price than the market average.

We used the above formula to calculate the adjusted price from hourly data from the Spanish Electricity market from 2008-2016. Results are shown in Table 2.

**Table 2.** Results for the adjusted price (AP), seasonal deviation (SD) and alignment ratio (AR). Source: Own elaboration based on data from Red Eléctrica Española and Operador del Mercado Ibérico de Energía (OMIE).

| **Variables** | JAN | FEB | MAR | APR | MAY | JUN | JUL | AUG | SEP | OCT | NOV | DEC |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Reference Price* | 52 | 52 | 52 | 52 | 52 | 52 | 52 | 52 | 52 | 52 | 52 | 52 |
| *Weighted monthly average electricity price for wind* | 40.8 | 35.3 | 33.6 | 32.7 | 39.4 | 44.8 | 48.1 | 47.8 | 49.1 | 47.3 | 42.9 | 45.1 |
| *Alignment ratio* | 87% | 84% | 87% | 88% | 93% | 95% | 97% | 97% | 94% | 93% | 91% | 91% |
| *Seasonal deviation* | 102% | 90% | 83% | 80% | 92% | 103% | 108% | 107% | 113% | 111% | 103% | 109% |
| *Adjusted price* | 46.0 | 39.3 | 37.5 | 36.6 | 44.5 | 50.8 | 54.2 | 53.8 | 55.6 | 53.7 | 48.7 | 51.6 |

Regarding the IS, it is important to highlight that the legal transition in Spain on renewable energies has a substantial impact on the calculations. The remuneration system has changed substantially since 2012. According to Royal Decree 413/2014, wind farms can receive public financial support during their first 20 years of operation. In this particular case, two wind farms (Cuadramón, El Perdón) have exceeded that time and therefore are only funded through electricity sales. The other two (Rubió and Río Almodóvar) will still receive an investment subsidy ("Retribución a la inversion") until that time is over. As the goal of the paper is to focus on specific climate change impacts and not to address financial implications of the new regulatory regime, and because of the long time-frame considered, baseline calculations assume that the investment subsidy is no longer in place. However, due to impact of removing it, calculations have also been made considering its continuation and results will be shown as an alternative scenario.

Regarding CAPEX and OPEX, several studies were evaluated, as shown in Table 3. For the official sources, an analysis commissioned by the Spanish Government [40] was chosen as the main reference, as it specifically addresses data from Spain, and has been used as a legal reference in the reform of the Spanish electricity market for renewable energies.

**Table 3.** CAPEX and OPEX values from literature (closest values to Spain have been included when available). Source: own elaboration.

| **Source** | **CAPEX** | **OPEX** |
|---|---|---|
| *Blanco 2009* [39] | 1100-1400 €/kW | 1.2-1.5 cent€/kWh |
| *De Jaeger et al 2011* [37] | <1125-1525 €/kW | 35-45 €/(kW*year) |
| *IRENA, 2012* [38] | 1882 USD/kW | 2.7 cUSD/kWh |
| *EWEA, 2009* [41] | 1227 €/kW | 1.2-1.5 c€/kWh |
| *WindFacts, 2009* [42] | 1200 €/kW | 1.2-1.5 c€/kWh |
| *IDAE- Boston Consulting Group, 2011* [43] | 1000-1300 €/kW | 1.72-2.16 c€/kWh |
| *IDAE- R. Berger, 2014* [40] | 1370-1550 €/kW | 41.3 €/(kW*year) |

When calculating the CAPEX, the cost of civil works and engineering was omitted, as these plants are already in operation. Therefore, the analysis only considered the investment required to replace the wind turbines. This equipment was assigned a physical lifespan of 25 years, based on the experience of the company.

The OPEX considers operations and maintenance, management, rental, insurances, electricity and self-consumption. Values provided by Acciona were aggregated as fixed operational costs, variable operational costs and representation costs.

National taxes (electricity generation and access tax) were considered, as well as regional taxes that exist in some regions. Local taxes on economic activities and property were not taken into account, and neither were taxes that are neutral to producers (such as the Added Value Tax or the Special Tax on Electricity).

For both incomes and costs, a *ceteris paribus* approach was used, so that unitary costs and electricity prices are constant over time. This method is intended to maintain a focus on the singular goal of the paper, which is to quantify the impact of climate change on wind electricity, not to forecast electricity prices or evolution of costs. Said variables may change substantially over the time range of the projections (2018-2065) therefore complicating an assessment of the specific variable being quantified, as explained in a previous paper [31].

Likewise, the physical characteristics of the farms was assumed to remain constant, with no adaptation measures.

## 3. Projection

### *3.1. Results*

Historical average wind speed is shown in Table 4, together with expected changes in the average for both RCPs. A decline is expected in Cuadramón and Rubió, and this decrease intensifies with time (near future versus mid century). Río Almodóvar shows increases in average wind speed, while in El Perdón both reductions and increases are seen. In almost all cases, there is a greater variation from the historical average under scenarios with higher concentrations of greenhouse gases in the atmosphere (RCP 8.5 compared to RCP 4.5), which is consistent with literature [6].

**Table 4.** Historical average wind speed versus medium and long-term projections. Source: own elaboration.

| Wind farm | RCP | Historical average (m/sec) | Average hourly variation (near future, 2018-2041) | Average hourly variation (mid century, 2042-2065) |
|---|---|---|---|---|
| *Cuadramón* | 4.5 | 7.07 | -3.5% | -3.6% |
| | 8.5 | 7.07 | -4.0% | -4.9% |
| *El Perdón* | 4.5 | 9.32 | -0.1% | 1.5% |
| | 8.5 | 9.32 | 1.0% | 0.2% |
| *Río Almodóvar* | 4.5 | 6.21 | 1.2% | 2.9% |
| | 8.5 | 6.21 | 2.5% | 3.9% |
| *Rubió* | 4.5 | 5.69 | -0.7% | -4.2% |
| | 8.5 | 5.69 | -1.2% | -4.1% |

With regards to production, as expected, trends are consistent with those seen for wind speed, however they are more pronounced. Table 5 compares historical average production with the annual average projected per farm. Production declines under all scenarios and future periods in Cuadramón and Rubió and increases in Río Almodóvar. El Perdón does not show a uniform trend; instead the evolution depends on the scenarios and future periods considered. The magnitude of the change is consistent with other case studies in literature, as explained above.

**Table 5.** Historical average production versus medium and long-term projections. Source: own elaboration.

| Wind farm | RCP | Historical average (MWh) | Average yearly variation (near future, 2018-2041) | Average yearly variation (mid century, 2042-2065) |
|---|---|---|---|---|
| *Cuadramón* | 4.5 | 47,562 | -4.7% | -4.5% |
| | 8.5 | 47,562 | -5.2% | -5.7% |
| *El Perdón* | 4.5 | 65,508 | -0.5% | 1.9% |
| | 8.5 | 65,508 | 1.0% | -0.1% |
| *Río Almodóvar* | 4.5 | 21,728 | 2.3% | 5.0% |
| | 8.5 | 21,728 | 3.6% | 6.5% |
| *Rubió* | 4.5 | 88,581 | -1.7% | -8.2% |
| | 8.5 | 88,581 | -2.5% | -8.0% |

Some studies highlight that the changing climate may affect intra-annual variability of wind generation, therefore limiting its reliability and predictability as a power source [6]. This variability was considered in the study, taking into account its potential economic and operational implications. Figure 2 shows seasonal variations between the reference period and future scenarios (an average of RCPs 4.5 and 8.5). A decline in production is expected in the winter and an increase in summer for all plants. Seasonal variations are most relevant at Rubió, with a very stark reduction in spring and increase in autumn. This change will become relevant in the economic analysis as the adjusted price is on average higher during summer and autumn. Rubió, for instance, will benefit from this fact according to the projections. The standard deviation of changes in wind speed throughout the different periods was analyzed, but no clear trend has been found in this regard.

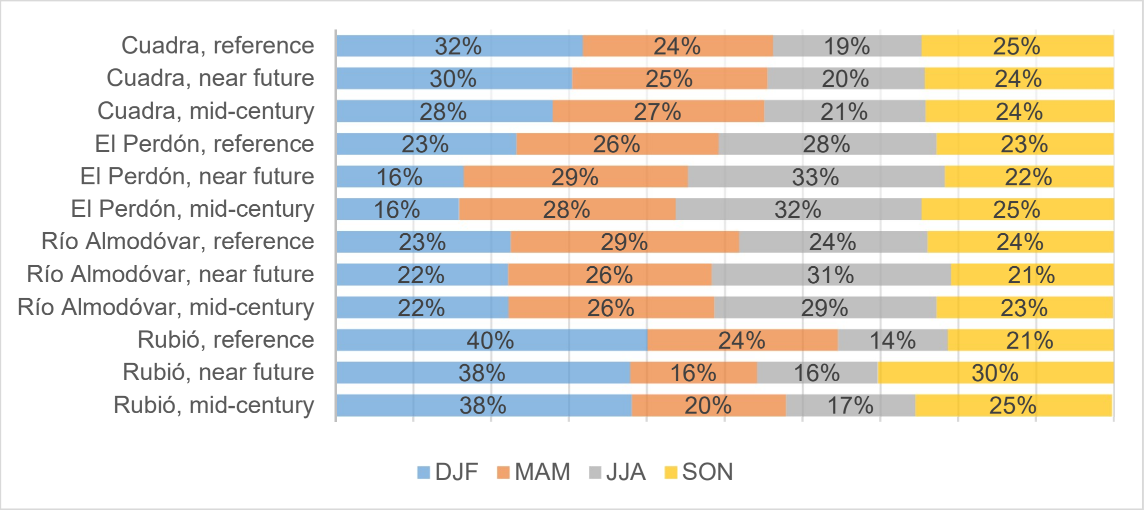

**Figure 2.** Seasonal production (in %) by wind farm. Source: own elaboration.

## 3.2. *Context in literature*

In order to evaluate the accuracy of the results, other sources of information were considered. On the one hand, some general projections of wind speed variations for Spain from existing literature were analyzed, although they cover large areas of the country rather than specific locations, as in this paper. There are no projections of electricity production, however there is a high correlation between wind speed and production, as shown above. On the other hand, a climate reanalysis was conducted in order to generate a historical series of wind speeds for each of the farms.

The results of this paper are compatible with trends shown in a study of projected changes in wind energy potentials in Iberia [26], despite some differences in timeframes (2041-2070 vs. 2042-2065 in this study) and variables (wind energy power vs. wind speed). The trend is consistent in terms of both increases (El Perdón, Río Almóvar) and decreases (Rubió, Cuadra) in average wind speed. The magnitude of these variations is also consistent and becomes more pronounced over time (from better to worse: Río Almodóvar, El Perdón, Cuadramón, Rubió).

A broad study of wind speed variability and future changes in the peninsula and Balearic Islands [25], reveals a decline in wind speed for all analysed clusters (2031-2050). Therefore, the results show the same tendency in Cuadramón and Rubió (although changes are less significant than in this paper), and a contrary trend in Río Almodóvar and in some periods in El Perdón. However, the analysis was oriented towards providing aggregate data for the Iberian Peninsula and its whole territory was divided in only 11 clusters (in fact El Perdón and Rubió are included in the same one).

The general trends are also consistent with other studies that provide a general overview of future changes in Europe. Most papers on this topic project wind speed decrease in the Mediterranean area (Rubió) [6,17,19–22,44,45] and many of them project an increase in the Gibraltar Strait area (Río Almodóvar) by mid-century [17,19,22,44]. Regarding the Ebro Valley area (El Perdón), the trend is less consistent with only some papers projecting an increase [22,44].

The climate reanalysis was conducted by Acciona for each of the farms, extrapolating the hourly wind speed series from 2010-2016 (measured data) back to 1987 (CFSR[3]) and to 1997 (Merra2[4]) using Vortex Series. The reanalysis provides simulated data combining global circulation models (GCMs) with meteorological measurements [46]. It is a widely used method to simulate large series of wind data, but correlation needs to be validated first, as accuracy on literature depends on specific variables such as altitude [32].

In this case, the correlation between the data obtained from reanalysis and historical data for 2010-2016 ranges from 50% to 85% depending on the model and the wind farm (with the lowest average correlation in Cuadramón, and CFSR providing better correlation than Merra2 in all wind farms). As shown in Figure 3, the reanalysis is not consistent in this farm, where historical data does not correspond with the reanalysis. The reanalysis does not provide projections, but as a larger dataset is available, a linear tendency has been calculated and extended for all farms. This is not a robust method to project wind speed but is useful for the operators of the plant as it shows whether the projections (RCP 4.5) are consistent with the historical trend, even if the time series are short. As shown in Figure 3 for CFSR, the tendencies are consistent in three of the parks and differ in Rubió. In almost all cases the slope of the change is higher than in the projections.

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[3] Climate Forecast System Reanalysis, by the National Centers for Environmental Prediction (NCEP).

[4] Modern-Era Retrospective analysis for Research and Applications, Version 2, by NASA.

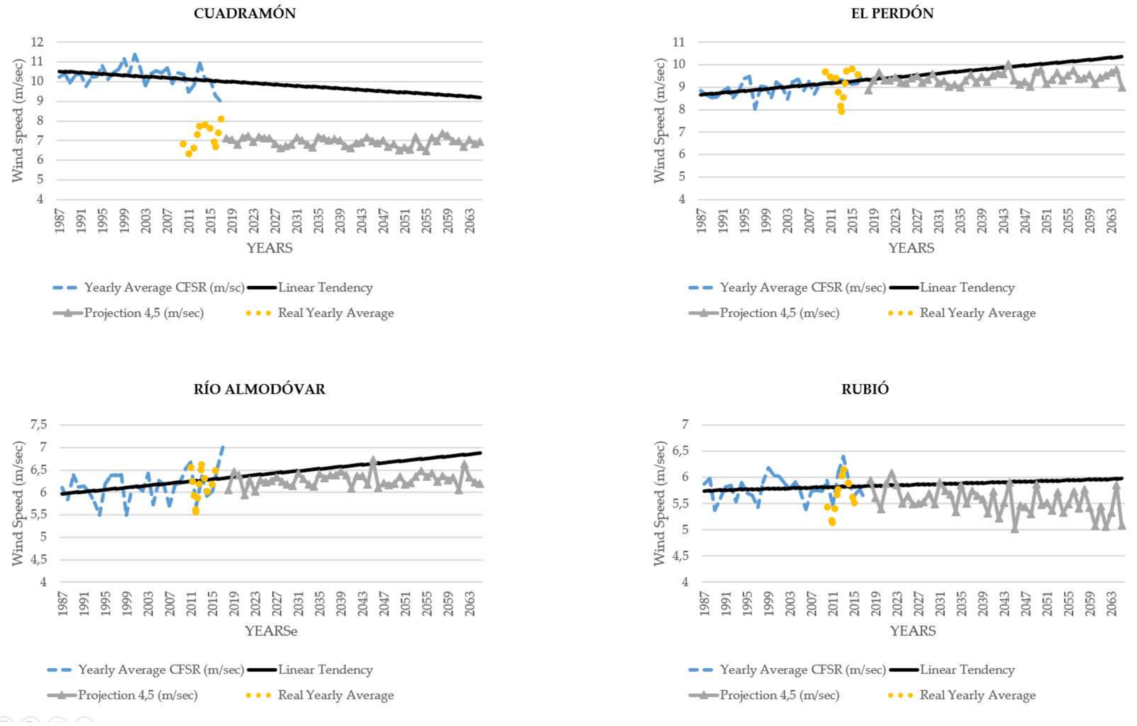

**Figure 3.** Reanalysis and projections. Source: Own elaboration based on data from Acciona.

## 4. Economic analysis

### 4.1. Analysis of operating margins

As we have assumed the removal of the investment subsidy as the baseline scenario, the results are very dependent on the production to power ratio (equivalent full load hours). There is a stark difference in performance between the four wind farms for this ratio, as shown in Table 6.

**Table 6.** Full load hours at each wind farm. Source: own elaboration based on data from Acciona.

| Wind farm | Period | Average annual production (MWh) | Installed capacity (MW) | Full load hours |
|---|---|---|---|---|
| *Cuadramón* | 2010-2016 | 47,562 | 18.75 | 2,537 |
| *El Perdón* | 2010-2016 | 65,508 | 20 | 3,275 |
| *Río Almodóvar* | 2011-2016 | 21,728 | 12.8 | 1,698 |
| *Rubió* | 2010-2016 | 88,581 | 49.5 | 1,790 |

The historical operating margins are consistent with these figures, as seen in Table 7. The Adjusted Price (AP) has been used both for the reference period and for the projections considering the goal of this paper. When using official sources, Cuadramón and El Perdón have the highest operating margins (15% and 38% respectively), whereas Río Almodóvar and Rubio have negative values (-14% and -10% respectively).

With respect to future projections, operating margins do not change dramatically, except in Río Almodóvar, which experiences an increase in production and improves its margins over time, particularly in the RCP 8.5 (which is more beneficial in terms of production and seasonality). In Rubió, due to expected reductions in production by the mid-century, operating profits are also substantially affected, reaching -14-15%, depending on the RCP. In the near future, changes in seasonality have a positive impact on income and operating margins. Cuadramón shows positive values, but in a smaller magnitude than El Perdón, in part due to the impact of regional taxes.

**Table 7.** Operating margins at each plant in the reference period and in the projections under official cost parameters. Source: own elaboration.

| | | RCP 4.5 | | RCP 8.5 | |
|---|---|---|---|---|---|
| **Wind farm** | **Historical average** | **Near future, 2018-2041** | **Mid century, 2042-2065** | **Near future, 2018-2041** | **Mid century, 2042-2065** |
| *Cuadramón* | 15% | 12% | 12% | 12% | 11% |
| *El Perdón* | 38% | 39% | 40% | 39% | 39% |
| *Río Almodóvar* | -14% | -8% | -5% | -6% | -4% |
| *Rubió* | -10% | -8% | -15% | -8% | -14% |

When using cost parameters provided by Acciona (Table 8), there are some differences in the starting point, with improvements in Cuadramón and Rubió. The evolution in future periods follows a similar evolution than the one shown above.

**Table 8.** Operating margins at each plant in the reference period and in the projections under cost parameters provided by Acciona. Source: own elaboration.

| | | RCP 4.5 | | RCP 8.5 | |
|---|---|---|---|---|---|
| **Wind farm** | **Historical average** | **Near future, 2018-2041** | **Mid century, 2042-2065** | **Near future, 2018-2041** | **Mid century, 2042-2065** |
| *Cuadramón* | 17% | 15% | 15% | 14% | 14% |
| *El Perdón* | 26% | 26% | 26% | 26% | 26% |
| *Río Almodóvar* | -29% | -24% | -22% | -22% | -20% |
| *Rubió* | -3% | -1% | -6% | -2% | -5% |

As stated in the methodology section (2), an alternative scenario has been designed, assuming that Río Almodóvar and Rubió receive the public investment subsidy for the period set in the regulatory framework. This scenario is not the most appropriate one to notice the influence of climate change, as the subsidy has a huge impact on the results, but it offers an interesting insight on the impact of the removal of public incentives to utilize renewable energies, which is much bigger than the physical impacts of climate change. Considering this variable, Table 9 shows how these two farms decrease their operating margins over time once the subsidy has been removed.

**Table 9.** Operating margins at each plant in the reference period and in the projections under official cost parameters. Source: own elaboration.

| | | RCP 4.5 | | RCP 8.5 | |
|---|---|---|---|---|---|
| **Wind farm** | **Historical average** | **Near future, 2018-2041** | **Mid century, 2042-2065** | **Near future, 2018-2041** | **Mid century, 2042-2065** |
| *Río Almodóvar* | 62% | 31% | -5% | 31% | -4% |
| *Rubió* | 45% | 14% | -15% | 13% | -14% |

As explained above, these results cannot be compared with other sources in literature, as existing studies rarely provide economic estimates and those that do, focus on a macro perspective, analyzing the impact on electricity prices [28,29], not on the perspective of the operator of the plant, that would be more interested in costs or operating margins.

### 4.2. Investment analysis

This analysis has been carried out regarding a hypothetical investment from scratch, taking into account all investments and the full set of capital costs. Therefore, civil works and engineering, as well as the full cost of the turbines will be included from the beginning. The investment subsidy has not been considered.

A period of 25 years has been considered (from 2018 to 2042), with a discount rate of 2%, consistent with other studies in the sector in Spain [31,47]. In one variation, there is no need for external funds and no opportunity costs have been included. In a second variation, financial costs have been added for 80% of the capital at a 6% discount rate under an equated yearly installment (equal payments during the loan life cycle to pay off interests and capital). The residual value in the last year accounts for the value of the initial investment excluding the cost of the turbines (civil works, electrical investment, land development and others).

The net present values for each wind farm, scenario and financing variation are shown in Table 10. The results are consistent with those of operating margins, with positive values for El Perdón and negative values for Río Almodóvar and Rubió. Cuadramón is closer to positive values (if the investment is done internally) and can achieve them if the lifetime of the turbines is extended beyond the 25 years. There is a clear difference in values when the financial costs are considered even if El Perdón remains with positive values. Rubió shows the worst results, in part due to its bigger size compared to the other wind farms.

**Table 10.** Net present values of investments in the wind farms. RCP 4.5 and 8.5. Source: own elaboration.

| | **RCP 4.5** | | **RCP 8.5** | |
|---|---|---|---|---|
| **Wind farm** | **100% internal** | **80% external** | **100% internal** | **80% external** |
| *Cuadramón* | -2,466,722 | -8,048,294 | -2,627,409 | -8,208,981 |
| *El Perdón* | 15,428,652 | 9,474,975 | 16,053,846 | 10,100,169 |
| *Río Almodóvar* | -6,722,617 | -10,532,970 | -6,436,118 | -10,246,471 |
| *Rubió* | -25,901,075 | -40,636,425 | -26,357,648 | -41,092,999 |

## 5. Discussion

This paper has analyzed the impact of changes in wind speed due to climate change in the long term. According to the results shown above, these changes will affect the production and operating margins of the selected wind farms. The projections were based on existing public information on future wind speed for two IPCC scenarios.

The results of the physical projections of this paper, as explained in section 3.2, are mostly consistent with other projections in this geographical area, both specific for the Iberian Peninsula and general for Europe. However, no studies have been conducted on the economic impacts of these changes from the perspective of the operator of the plant, so the results on operating margins and investment parameters cannot be compared with existing literature.

Due to the long-term framework of the assessment, certain methodological choices were made to avoid distortion. First, the analysis was based on operating margins rather than profits, to prevent the impact of discount rates. Second, a *ceteris paribus* approach was chosen for considering costs and incomes. This was done, as explained in a previous paper [31], to specifically highlight the impacts of climate change, which may be difficult to pinpoint when changes in costs and prices are considered over such a long period. This paper has also assumed that no adaptation measures will be undertaken. However changes in the design and operation of wind turbines are to be expected in the long term if changes in wind speed are confirmed over time [15].

Regarding the economic assumptions, this paper outlined two cost scenarios (official and company assumptions) and two income scenarios (with and without the investment subsidy). By doing so, it provides robustness to the results and a better understanding of the importance of the regulatory framework.

There are several uncertainties that could benefit from future research, such as the fact that only changes in wind speed have been considered here. Changes in wind direction and other variables such as extreme wind events or icing of the blades may be relevant as well [7].

The resolution of the bins for the power curves (0.5 m/sec) was based on existing information and is consistent with current practice in the sector, however this might underestimate the cumulative impact of small changes in wind speed.

## 6. Conclusions

This study has shown that climate change may affect wind speed and, therefore, wind production in Spain. Four wind farms were chosen for their characteristics and geographical locations, where existing literature suggests variations in the resource.

According to the results, changes in average wind speed vary between wind farms. A decrease in speed is to be expected in Cuadramón and Rubió for all scenarios and time periods. In Río Almodóvar, an increase is projected, whereas results for El Perdón depend on the time frame and scenario. The greatest decrease is projected for Rubió and Cuadramón, with reductions of around 5% for the period 2042-2065.

Regarding annual production, results are consistent with those for wind speed, but in a greater magnitude. Again, Rubió shows the most significant decrease in production, at around 8% for the period 2042-2065. Increases in Rio Almodóvar are projected to be between 5% and 6% for the same period. Concerning seasonality, projections show an increase in production at all plants during the summer, and a decline during the winter.

These changes in production affect the operating margins and investment parameters of the plants. Considering the economic assumptions made in this analysis, said parameters are highly influenced by the equivalent full load hours of the farms. The production to installed power ratio during the historical period in El Perdón (3275) is nearly double that of Río Almodóvar (1698), and therefore has a clear impact on calculated operating margins. Due to the expected increases in production, changes in operating margins are relevant in both Río Almodóvar and Rubió. Only slight changes are projected for the other plants.

These conclusions will benefit from further research and broadened information, as described in the section Discussion (5). More accurate projections that consider further climate variables will improve the quality of the results

With respect to conclusions related to public policy, this paper does not foresee dramatic changes in wind production at the analyzed plants. Changes in the regulatory framework have a higher impact on the analyzed plants, according to the calculations. As shown in the investment analysis, new farms such as Rubió and Río Almodóvar may not be profitable without the public investment subsidy.

In any case, wind energy generation is the most important source of renewable electricity in Spain [48], and the evolution of wind speed should be monitored to confirm the conclusions of existing climate projections.

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# The influence of climate on electricity demand in the Basque Country in the context of climate change[1]

Abstract: This article analyzes the sensitivity of electricity demand by sector to temperature, in the context of climate change. The paper outlines a methodology to incorporate climate variables into energy decision making. This methodology is based on the evolution of the thermal distance on cold and warm days with respect to established thresholds (Heating Degree Days and Cooling Degree Days) and its influence on demand. This approach has been tested in the Basque Country. Results show that the residential sector is the most sensitive to these changes, and future demand is projected according to multiple climate change scenarios. Due to the greater statistical significance of temperature differences on cold days, and the current limited use of air conditioning, it is estimated that residential demand could fall by as much as 4%, which could translate to nearly 20 million euros in annual savings and emission reductions of around 30,000 t. of CO2 per year.

Keywords: climate change, adaptation to climate change, energy demand, energy economics.

## 1. Introduction

Due to its use of non-renewable fossil fuels, the electricity sector contributes substantially to climate change and, in turn, may find itself relevantly impacted by it [1,2]. These impacts are not limited to production and may include repercussions for distribution networks and demand as well [1,3–5].

Multiple studies have shown that electricity demand is highly sensitive to variations in temperature and, therefore, that climate change could bring about changes in consumption [6–8]. Generally speaking, the relationship between temperature and energy consumption is U-shaped, meaning that increases in consumption correspond with both very low and very high temperatures [9–12].

Logically, the influence of climate depends in large part on the location of the area of study and its energy sources [9]. The relationship between climate change and temperature is positive in some locations and negative in others, depending on geography and climatic conditions [7].

In Europe, several models suggest that effects on demand will be greater than on production, [13] and that meteorological forecasts may be useful for estimating electricity demand in the short and mid-term [14,15]. With respect to the long-term impacts of climate change, some studies project a reduction in demand for electricity, as the impact of decreased consumption in the winter is expected to be greater than that of increased consumption in the summer [16–18] . This can lead to an overall reduction of up to 22% in the long-term [17]. This decrease in demand will also be seen in Southern Europe, including Spain. However, another paper predicts a neutral overall effect [12].

Spain is made up of various climatic regions, which have an important impact on the demand structure [19]. Several studies have analyzed the factors which most significantly influence demand, such as climate, with a particular emphasis on the residential sector [19,20].

In the Basque Country, an autonomous region in Spain, the demand for electricity is characterized by the important role of the industrial sector, which makes up 55% of all consumption, followed by the service sector (24%) and the residential sector (19%) [21]. Of the three provinces that

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form this autonomous region, Biscay accounts for nearly half of all electricity consumption (47%), which is consistent with its share of the population (52%) and contribution to GDP (50%)[2].

Regarding climate, the Basque Country is generally more temperate than the rest of Spain, although projections do show an increase in temperatures. This translates to fewer cold days, more warm days, and a general increase in extreme values [22]. Studies carried out in colder countries predict a significant decrease in heating consumption as the frequency and intensity of cold days decrease. In some cases, electricity demand may fall by as much as 14% by the middle of the century [23].

The objective of this article is to outline a methodology to link climate and energy data and to analyze to what extent electricity demand is vulnerable to variations in temperature and, in turn, to project how it may evolve under given climate change scenarios. The methodology is based on the calculation of the thermal differences between daily average temperature and comfort thresholds. It will be tested in the residential sector in the Basque Country.

To that end, the paper is structured as follows: section two offers a summary of the methodology used and the scope of the study. Section three analyzes the composition and evolution of demand. Section four looks at changes in temperature in relation to the methodology used. Section five focuses on the correlation between electricity consumption and climate. Section six goes on to predict how temperature changes may impact demand in the residential sector in the future. The article closes with a discussion of the results within the framework of energy policy in the Basque Country and its European counterpart.

## 2. Methodology

The methodology used in this paper can be summarized in five steps:

1. **Gathering of data on electricity demand.**

The use of data with high seasonal (and sectoral) resolution is necessary to trace climate influence on demand. Then data must be aggregated to fit with climate information.

2. **Gathering of climate information and calculation of Heating Degree Days and Cooling Degree Days.**

Many sources in literature analyze the relationship between climate variables and energy demand based on the calculation of deviations in temperature with respect to what would be considered comfort temperatures. In the case of Spain, this methodology has been used to analyze the sensitivity of demand in the residential sector to these deviations [19,20,24]. This provides better results than simply using average temperatures, due to the nonlinear relationship between changes in temperature and demand [19].

Therefore, cooling degree days (CDD) and heating degree days (HDD) are usually defined as the sum of the temperature differentials on days when the average temperature deviates from certain cold or warm thresholds, within a given period. They are calculated using the following methodology [17,20,25,26]:

$$HDD_{year} = \sum_{days} max\,(0, (Ct - At))$$

$$CDD_{year} = \sum_{days} max\,(0, (At - Ct))$$

Where:
HDD = Heating Degree Days.
CDD= Cooling Degree Days.

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[2] Data from the Spanish Statistical Office (INE), 2015.

Ct= comfort temperature expressed in ºC. This paper uses 18º and 26ºC, as these are the thresholds used by the State Meteorological Agency (AEMET) for its projections, but a sensitivity analysis will be conducted below.

At= average daily temperature expressed in ºC.

To calculate the HDD and CDD, meteorological data from the State Meteorology Agency (AEMET) were used for the three provincial capitals, as they contain the largest concentrations of population and economic activity.

**3. Correlation and dependency analysis of climate and energy information.**

This paper analyzes the correlation between these data and sector electricity consumption from 2012 to 2017 (monthly data). In order to use the same sector classifications, and to contrast consumption data with other variables, consumption will be grouped into 16 sectors.

Two-tailed significance has been analyzed as well to test the statistical significance of the correlation.

**4. Projection of HDD and CDD and energy demand.**

The evolution of Heating Degree Days and Cooling Degree Days can be done by using climate models with a right level of geographical disaggregation. In this paper, regional projections from EMET/Euro-CORDEX have been used via the Adaptecca platform for each province of the Basque Country for the RCP 4.5 and 8.5 scenarios of the 5AR of the IPCC [27]. These scenarios consolidate hypotheses on the main variables affecting climate. RCP 4.5 models a moderate increase in surface air temperature (between 1.1º and 2.6ºC), which may be consistent with international climate change policy scenarios. RCP 8.5, on the other hand, suggests greater future temperature increases (between 2.6º and 4.8ºC).

Given that the residential sector shows the closest correlation, as will be demonstrated below, demand for this sector will be projected based on the expected evolution of HDD and CDD.

**5. Calculation of costs or benefits and emissions.**

Depending on the results of the projection, there may be costs (when demand increases) or benefits (when demand decreases). In any case, the change in consumption should take into account that electricity prices differ between economics sectors.

Regarding emissions, we estimate them by considering the increase or decrease in demand and the average carbon intensity of electricity generation (Green-House Gas Emissions, GHG) in the energy system per unit of electricity produced). As this paper is focused on highlighting the specific impact of climate change in the existing energy system, we will use the current carbon intensity, according to the latest published data on emissions of the Spanish electricity system (from 2017 [28]). Projected future emissions could be used as well based on energy strategies or climate goals.

## 3. Electricity demand in the Basque Country

Data from the Basque Energy Agency (EVE, Basque Government) will be used in this paper. It provides a short time frame (2012-2017) but with a monthly resolution. These data are consistent with those from the Spanish Ministry for the Ecological Transition. The Ministry offers a wider temporal scope but only annual resolution, so it is not so useful for the purposes of this paper. While there are small differences between these sources in certain sectors, the global results are generally consistent, as shown in Figure 1.

In all three provinces, there is a noticeable shift coinciding with the 2008 economic crisis. Álava and Biscay hit their peak electricity consumption in 2008, and Gipuzkoa in 2007. Afterward, consumption dropped consistently in Biscay and Gipuzkoa, with Álava being the only province with higher consumption in 2017 than in 2000.

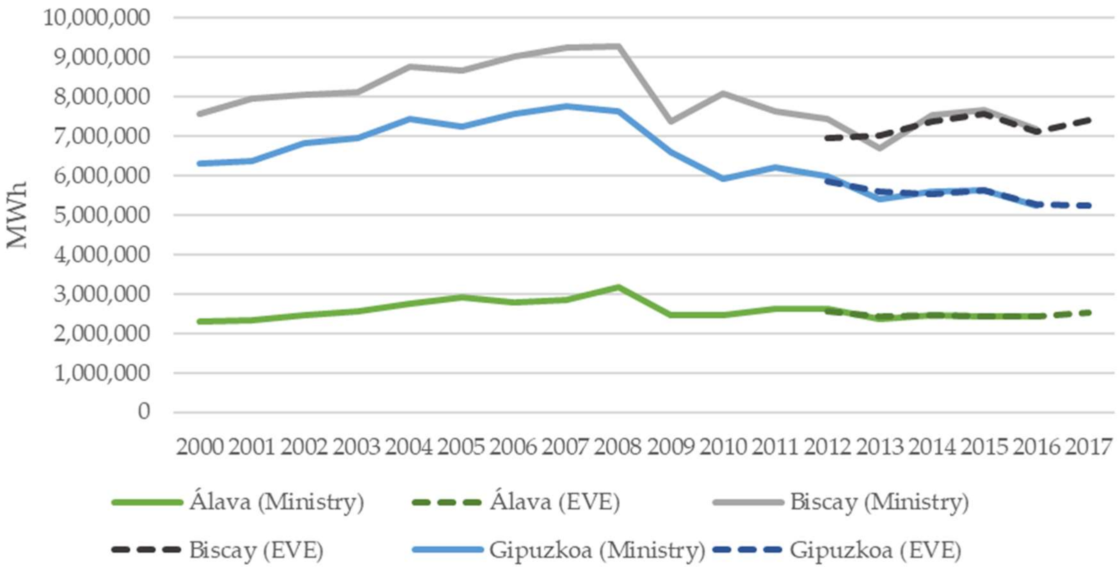

**Figure 1.** Electricity demand in the three provinces from 2000 to 2017 with data from EVE and the Ministry for the Ecological Transition.

The sector structure of electricity consumption does not vary significantly across the three provinces, as can be seen in Table 1. Metallurgy stands out as the highest consumer of electricity in all three provinces from 2012-2017, making up nearly 25% of the total, followed in all three provinces by residential. In absolute terms, Biscay is the province with the highest consumption, followed by Gipuzkoa and Álava. Seasonally, there are no significant differences between provinces and a relatively consistent trend throughout the year, although spring shows slightly higher levels of consumption across the board.

**Table 1.** Sector distribution of electricity demand from 2012-2017. Source: EVE.

| | **Electricity consumption from 2012 to 2017(GWh)** | | | | **Sectoral distribution %** | | | |
|---|---|---|---|---|---|---|---|---|
| **SECTOR** | **ÁLAVA** | **BISCAY** | **GIPUZKOA** | **TOTAL** | **ÁLAVA** | **BISCAY** | **GIPUZKOA** | **TOTAL** |
| *Agriculture, forestry and fishing* | 63 | 88 | 134 | 285 | 0.4% | 0.2% | 0.4% | 0.3% |
| *Extractive industries* | 788 | 868 | 658 | 2,314 | 5.3% | 2.0% | 2.0% | 2.5% |
| *Electricity, gas and steam* | 1,418 | 385 | 165 | 1,968 | 9.6% | 0.9% | 0.5% | 2.2% |
| *Food, drink and tobacco* | 454 | 561 | 691 | 1,705 | 3.1% | 1.3% | 2.1% | 1.9% |
| *Textile, clothing, leather and footwear* | 11 | 46 | 124 | 181 | 0.1% | 0.1% | 0.4% | 0.2% |
| *Wood, paper and graphic arts* | 230 | 1,750 | 4,450 | 6,430 | 1.6% | 4.0% | 13.4% | 7.0% |
| *Rubber and plastics* | 405 | 963 | 859 | 2,227 | 2.7% | 2.2% | 2.6% | 2.4% |
| *Chemical, petrochemical and pharma* | 381 | 3,710 | 1,225 | 5,317 | 2.6% | 8.5% | 3.7% | 5.8% |
| *Metallurgy* | 3,369 | 11,788 | 8,199 | 23,356 | 22.7% | 27.1% | 24.7% | 25.6% |
| *Electric equipment, machinery, vehicles, transportation materials* | 1,981 | 3,232 | 4,405 | 9,618 | 13.4% | 7.4% | 13.3% | 10.5% |
| *Construction and public works* | 94 | 345 | 233 | 673 | 0.6% | 0.8% | 0.7% | 0.7% |
| *Transportation and storage* | 541 | 1,946 | 1,017 | 3,504 | 3.6% | 4.5% | 3.1% | 3.8% |

| | **Electricity consumption from 2012 to 2017(GWh)** | | | | **Sectoral distribution %** | | | |
|---|---|---|---|---|---|---|---|---|
| **SECTOR** | **ÁLAVA** | **BISCAY** | **GIPUZKOA** | **TOTAL** | **ÁLAVA** | **BISCAY** | **GIPUZKOA** | **TOTAL** |
| *Hospitality* | 381 | 1,372 | 931 | 2,684 | 2.6% | 3.2% | 2.8% | 2.9% |
| *Commerce and services* | 1,347 | 4,220 | 2,792 | 8,360 | 9.1% | 9.7% | 8.4% | 9.1% |
| *Residential* | 2,197 | 8,600 | 5,239 | 16,036 | 14.8% | 19.8% | 15.8% | 17.5% |
| *Public service and administration* | 1,167 | 3,560 | 2,007 | 6,734 | 7.9% | 8.2% | 6.1% | 7.4% |
| *Total* | 14,829 | 43,437 | 33,128 | 91,393 | 100.0% | 100.0% | 100.0% | 100.0% |

In the residential sector, per capita consumption during this period is similar in all three provinces, with the highest relative consumption in Biscay (1.24 kWh per capita), followed by Gipuzkoa (1.22) and, lastly, by Álava (1.13)[3]. Nevertheless, these differences do not exceed 10% and remain stable, in relative terms, over time.

The Basque residential sector is characterized by the popularity of natural gas for heating. 59% of households use some type of heating system with natural gas, while 22% use electricity, 14% gas oil, 7% others, and 9% that do not use any heating system at all [29]. Some households use a combination of these heating systems. The percentage of Basque households using electricity for heating is similar to the average for the rest of Spain, while that of natural gas is higher [30].

Heating makes up 30% of all electricity consumption in Basque households [29]. The majority of homes are flats (74%), with fewer single-family homes (26%) than the Spanish average [31]. Just 1.7% of households have air conditioning, with the greatest relative number of these in Gipuzkoa (3.5%, [29]).

## 4. Climate evolution

In studies of climate zones using the Köppen-Geiger classification, the Basque Country is usually included in the Cfb zone (temperate climate with no dry season and mild summers)[30,31]. If examined more closely, however, a large part of Álava is actually located in the Csb zone (temperate climate with dry, mild summers) [32]. In other words, Biscay and Gipuzkoa are impacted by the North Atlantic, while Álava has a more continental climate [24,29,33]. This translates to more frequent precipitation and milder temperatures in the former two.

Meteorological data from the State Meteorology Agency (AEMET) were used for the three provincial capitals, as they contain the largest concentrations of population and economic activity. According to these data, and in keeping with the previously mentioned thresholds, Vitoria is the city with the highest number of HDDs, followed by San Sebastian and Bilbao. With respect to CDD, the inverse is true, led by Bilbao and followed by San Sebastian and Vitoria.

The AEMET data for each location (with distinct start periods depending on the available data) show an upward trend in CDD and a downward trend in HDD in all three cities. This is in the context of increasing average temperatures over time, albeit with varying intensity, as can be seen in Figure 2. The trend is shown due to the annual weather variability and has been calculated by using the method of least squares. This trend is consistent with the context of increasing average temperatures over time, albeit with varying intensity. There is also a notable difference between the absolute quantity of CDD and HDD recorded, as seen in the different scales used for the left (HDD) and right (CDD) axes, respectively.

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[3] According to energy data from EVE and official population data from the Spanish Statistical Office (INE).

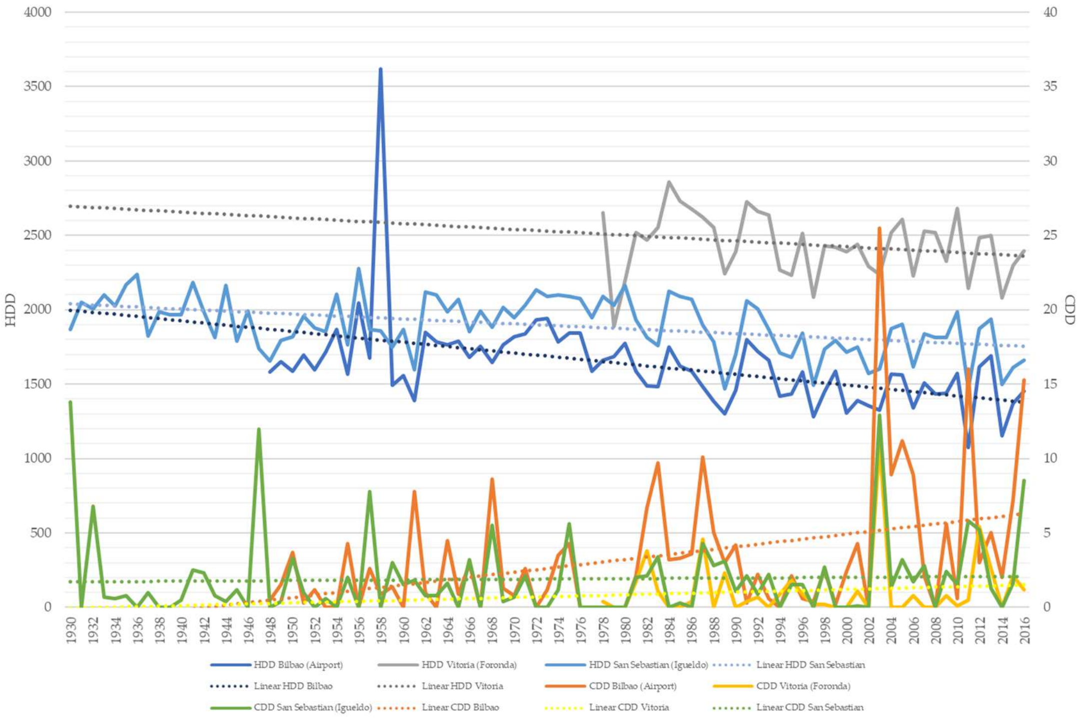

**Figure 2.** Quantity of HDD and CDD per city over time. Source: Own elaboration based on data from the State Meteorological Agency (AEMET).

## 5. Correlation between temperature and energy consumption

The indicators of HDD and CDD have been aggregated and used to analyze their correlation with demand in the various sectors. As can be seen in Table 2, correlations tend to be modest, but the residential sector shows the clearest one, followed by public service and administration and commerce and services. The latter sector may be influenced by a decreased demand for services during the winter months, coinciding with the highest concentration of HDD. In many sectors, particularly industrial, electricity consumption may be determined by non-climate variables, mostly production. More information on the analysis of correlation and statistical significance can be found in the supplementary materials.

**Table 2.** Correlation between demand and HDD+ CDD by province and sector. Correlations greater than 50% have been highlighted. Source: own elaboration.

| SECTOR | Álava | Biscay | Gipuzkoa | Average |
|---|---|---|---|---|
| *Agriculture, forestry and fishing* | -70% | -14% | -10% | -31% |
| *Extractive industries* | -8% | -42% | -12% | -21% |
| *Electricity, gas and steam* | 5% | 11% | -7% | 3% |
| *Food, drink and tobacco* | -47% | -28% | -58% | -45% |
| *Textile, clothing, leather and footwear* | 22% | -12% | 8% | 6% |
| *Wood, paper and graphic arts* | 1% | -19% | -6% | -8% |
| *Rubber and plastics* | 10% | 8% | -11% | 2% |
| *Chemical, petrochemical, and pharma* | 4% | -22% | -12% | -10% |
| *Metallurgy* | 20% | 2% | 23% | 15% |
| *Electric equipment, machinery, transportation materials* | 21% | 20% | 22% | 21% |
| *Construction and public works* | 41% | 27% | 33% | 34% |
| *Transportation and storage* | 62% | 16% | 37% | 38% |
| *Hospitality* | -33% | -40% | -68% | -47% |

| SECTOR | Álava | Biscay | Gipuzkoa | Average |
|---|---|---|---|---|
| *Commerce and services* | 53% | 19% | 44% | 39% |
| *Residential* | 50% | 68% | 69% | 63% |
| *Public service and administration* | 64% | 46% | 59% | 56% |
| *Total demand* | 36% | 28% | 48% | 37% |

In this analysis, 18º and 26ºC have been used as thresholds as explained above. For the residential sector, the sensitivity of these correlations has been analyzed by modifying the established thresholds of HDD and CDD according to the most relevant values in literature [26], as seen in Table 3. The differences, while not very significant, do indicate slightly higher average correlations when 18ºC is used as the threshold for the calculation of HDD, even if the values in Álava are slightly lower.

**Table 3.** Analysis of sensitivity of correlations in the residential sector to HDD and CDD thresholds. Source: own elaboration.

| | HDD 13 | | | | HDD 15 | | | | HDD 18 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | ÁLAVA | BISCAY | GIPUZKOA | AVERAGE | ÁLAVA | BISCAY | GIPUZKOA | AVERAGE | ÁLAVA | BISCAY | GIPUZKOA | AVERAGE |
| CDD 22 | 52% | 60% | 70% | 61% | 51% | 66% | 70% | 62% | 50% | 68% | 69% | 63% |
| CDD 24 | 53% | 63% | 70% | 62% | 51% | 67% | 70% | 63% | 50% | 68% | 69% | 63% |
| CDD 26 | 53% | 64% | 70% | 62% | 51% | 67% | 70% | 63% | 50% | 68% | 69% | 63% |

Most likely, the expansion of the natural gas network has contributed to lower sensitivity in this sector, although the network has not changed significantly in recent years[4] . Recent policies point to the future electrification of heat as a way to reduce greenhouse gas emissions, which could reverse this trend [36,37].

## 6. Future climate projections

Climate projections for the Basque Country predict an increase in average temperatures from 1º to 5ºC by the end of the century, depending on the scenario [22]. This increase would be uniform, although slightly less on the coast than inland. As a result, the indexes linked to days with low temperatures would also decrease, while those linked to days with high temperatures would tend to increase.

In terms of the Köppen-Geiger climate zones, the projections do not forecast any meaningful change, although the southern part could find itself within the Cwb climate zone (dry climate with warm summers) by the end of the century [38].

The change in projected HDD and CDD by AEMET compared with the reference period of 2012-2017 has been calculated, as shown in Figure 3.

RCP 4.5 shows a gradual decrease in HDD, while the projection for scenario 8.5 is less linear but more pronounced at the end of the century. Differences between provinces are not considerable, although Biscay tends to be the province with the greatest decrease.

The projected rise in CDD is substantially more pronounced. Again, RCP 8.5 reveals a less linear evolution, but is more pronounced from 2046-2070. In this case, Álava experiences the highest increase in CDD, with greater differences between the provinces than for HDD.

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[4] Annual Reports on the retail market by the National Commission on Markets and Competition show a small decrease in household natural gas consumption from 2010 to 2016: https://www.cnmc.es/ambitos-de-actuacion/energia/mercado-gas

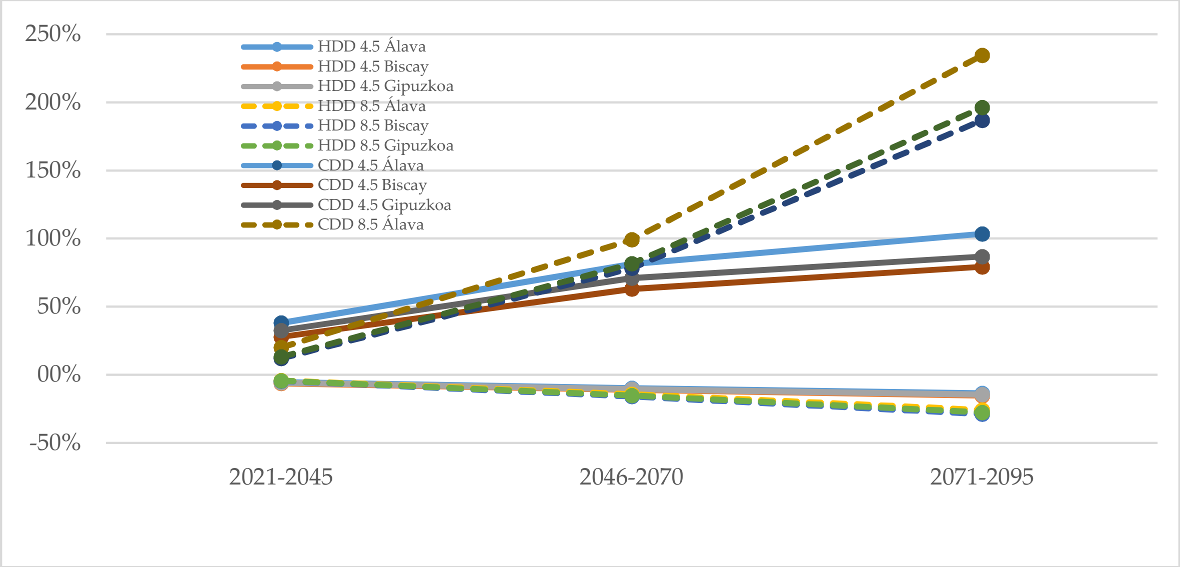

**Figure 3.** The average projected evolution of HDD and CDD per province compared with the reference period (2012-2017). Source: own elaboration based on data from the State Meteorological Office (AEMET).

Nevertheless, as explained below, it should be noted that the ratio of CDD to HDD barely reaches 1% historically and, despite the expected increase, will hardly surpass 5% by 2100 even in the most extreme scenarios.

The future decrease in consumption in the residential sector that could result from changes in HDD and CDD has been quantified. The thresholds used for the reference period are 18ºC for HDD and 26ºC for CDD, in accordance with AEMET projections.

The results are shown in Table 4. Reductions in annual consumption start at 1 % in all provinces and scenarios and by the end of the century they range from 2% to 4%, depending on the province and scenario. Reductions, as expected, are higher under a more intense climate scenario (RCP 8.5) and in the long term. Variations tend to be slightly higher, in relative terms, in Gipuzkoa, compared to other provinces. In economic terms, using RCP 8.5 and at current electricity prices[5], this could mean annual savings of nearly 20 million euros between the three provinces by the end of the century.

With respect to CO2 emissions, total reductions for the three provinces could reach 30,000 tons annually under the RCP 8.5 scenario[6].

**Table 4.** The projected decrease in consumption, economic savings, and emissions reductions in the residential sector for the three provinces compared to the reference period (2012-2017). Source: own elaboration.

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[5] Prices provided by the Eurostat database during the first semester of 2018 have been used as reference: https://ec.europa.eu/eurostat/web/energy/data/database

[6] A reduction in the emission mix is to be expected in the future according to the draft Strategic Energy and Climate Framework (2019) and European climate and energy goals. If these goals are met, emission reductions would be lower.

**Álava**

| | *2021-2045 vs. 2012-2017* | | | | *2046-2070 vs. 2012-2017* | | | | *2071-2095 vs. 2012-2017* | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Scenario** | **Annual Reduction (MWh)** | **Reduction (%)** | **Annual savings (€ 2018)** | **CO2 reductions (t)** | **Annual Reduction (MWh)** | **Reduction (%)** | **Annual savings (€ 2018)** | **CO2 reductions (t)** | **Annual Reduction (MWh)** | **Reduction (%)** | **Annual savings (€ 2018)** | **CO2 reductions (t)** |
| *RCP 4.5* | 3,663 | 1% | 686,095 | 1,023 | 6,065 | 2% | 1,135,905 | 1,694 | 8,003 | 2% | 1,498,956 | 2,235 |
| *RCP 8.5* | 2,987 | 1% | 559,498 | 834 | 8,375 | 2% | 1,568,581 | 2,339 | 13,801 | 4% | 2,584,985 | 3,855 |

**Biscay**

| | *2021-2045 vs. 2012-2017* | | | | *2046-2070 vs. 2012-2017* | | | | *2071-2095 vs. 2012-2017* | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Scenario** | **Annual Reduction (MWh)** | **Reduction (%)** | **Annual savings (€ 2018)** | **CO2 reductions (t)** | **Annual Reduction (MWh)** | **Reduction (%)** | **Annual savings (€ 2018)** | **CO2 reductions (t)** | **Annual Reduction (MWh)** | **Reduction (%)** | **Annual savings (€ 2018)** | **CO2 reductions (t)** |
| *RCP 4.5* | 13,258 | 1% | 2,483,217 | 3,703 | 23,126 | 2% | 4,331,484 | 6,460 | 32,268 | 2% | 6,043,750 | 9,013 |
| *RCP 8.5* | 9,881 | 1% | 1,850,690 | 2,760 | 33,189 | 2% | 6,216,365 | 9,271 | 59,405 | 4% | 11,126,557 | 16,594 |

**Gipuzkoa**

| | *2021-2045 vs. 2012-2017* | | | | *2046-2070 vs. 2012-2017* | | | | *2071-2095 vs. 2012-2017* | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **Annual Reduction (MWh)** | **Reduction (%)** | **Annual savings (€ 2018)** | **CO2 reductions (t)** | **Annual Reduction (MWh)** | **Reduction (%)** | **Annual savings (€ 2018)** | **CO2 reductions (t)** | **Annual Reduction (MWh)** | **Reduction (%)** | **Annual savings (€ 2018)** | **CO2 reductions (t)** |
| *RCP 4.5* | 13,503 | 2% | 2,529,142 | 3,772 | 21,597 | 2% | 4,045,074 | 6,033 | 28,495 | 3% | 5,337,103 | 7,960 |
| *RCP 8.5* | 12,813 | 1% | 2,399,897 | 3,579 | 23,947 | 3% | 4,485,245 | 6,689 | 34,860 | 4% | 6,529,202 | 9,737 |

**Basque Country (all provinces)**

| | *2021-2045 vs. 2012-2017* | | | | *2046-2070 vs. 2012-2017* | | | | *2071-2095 vs. 2012-2017* | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **Annual Reduction (MWh)** | **Reduction (%)** | **Annual savings (€ 2018)** | **CO2 reductions (t)** | **Annual Reduction (MWh)** | **Reduction (%)** | **Annual savings (€ 2018)** | **CO2 reductions (t)** | **Annual Reduction (MWh)** | **Reduction (%)** | **Annual savings (€ 2018)** | **CO2 reductions (t)** |
| *RCP 4.5* | 30,424 | 1% | 5,698,454 | 8,498 | 50,787 | 2% | 9,512,463 | 14,187 | 68,766 | 3% | 12,879,809 | 19,208 |
| *RCP 8.5* | 25,681 | 1% | 4,810,085 | 7,174 | 65,511 | 2% | 12,270,191 | 18,299 | 108,066 | 4% | 20,240,744 | 30,186 |

Results showing that reductions in HDD will have a greater impact than increases in CDD are consistent with existing literature as will be later discussed. The increase in warm days is not expected to have a notable impact on total consumption for the sector in the Basque Country over the next 50 years. Both the historical and projected ratios of thermal differentials on warm days to cool days are small in the Basque Country compared to other regions in Spain, as can be seen in Figure 4.

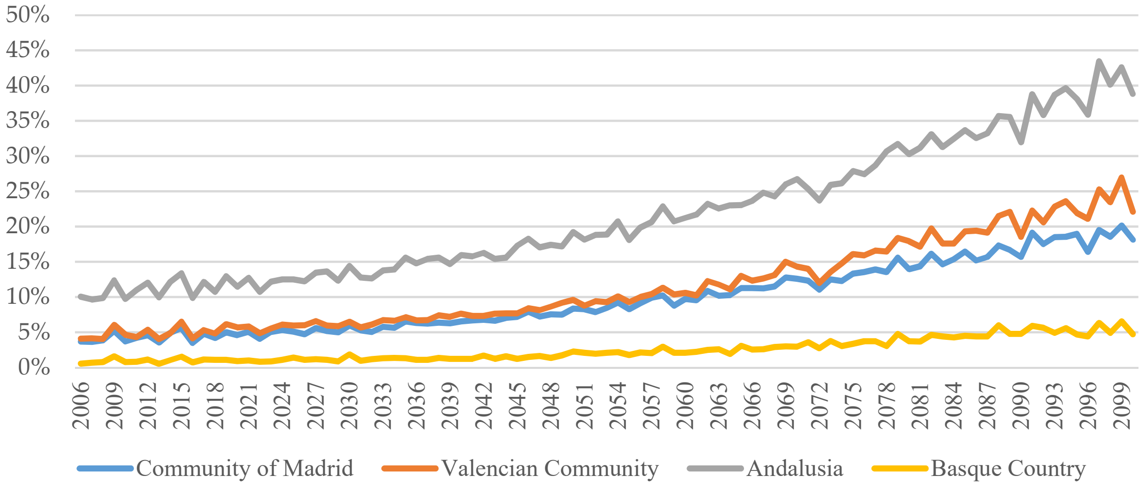

**Figure 4.** Historical and projected (RCP 8.5) ratio of CDD/HDD in four autonomous regions. Source: own elaboration based on data from AEMET/ EURO-CORDEX.

## 7. Discussion

This article has analyzed the sensitivity of electricity demand in the Basque Country to temperature in order to project how climate change may influence it. The results show that the residential sector is the most sensitive to temperature changes, particularly on cold days.

A methodology based on HDD and CDD has been used. In historical climate data, a reduction in HDD and an increase in CDD can be seen in all three provincial capitals, and this trend continues in future projections.

The impact of expected temperature changes could be both important and positive for the residential sector. Scenarios of more significant climate change (RCP 8.5) predict a drop in consumption of as much as 4% by the end of the century, which could translate to nearly 20 million euros in annual savings.

From a policy development standpoint, this article stresses the importance of taking variations in climate into account during the planning and design of energy infrastructure. This topic becomes very relevant due to existing European, Spanish and Basque targets on emissions and energy consumption. With the current state of technologies, meeting the most ambitious long-term emissions targets can only be achieved through the expansion of the renewable electricity generation and through the substitution of other sources of thermal energy (particularly natural gas and traditional fossil fuels) with electricity.

The electrification of heating systems would give the results of this study greater quantitative relevance as the elasticity of electricity consumption to climate variables might become key. This transformation is already included in the Energy Plan of the autonomous region, with a particular emphasis on the transportation sector [36]. At the European level, the contribution of electricity to total energy demand would practically double by 2050, according to the European Energy Roadmap [37].

Energy efficiency can play a very relevant role in this context as well. As heating and cooling devices become more efficient, additional energy needs would require less marginal consumption. The reduction of the energy intensity is a relevant goal in energy and climate planning at European, Spanish and Basque levels and measures to foster efficiency at the residential sector are an integral part of it.

Along these same lines, as temperature increases, a greater prevalence of air conditioning systems is logically expected, making demand more sensitive to temperature changes in the summer. Even so, some studies predict a net decrease in consumption including in Southern European countries, due to the greater relative importance of temperature differentials on cold days [17,18].

However, another paper looking at all sectors suggests an increase in average daily electricity consumption in Spain of between 0.2% and 5.6% according to RCP 4.5 or 8.5, respectively [12]. The trends of this study are not, however, homogeneous for countries located in the same climate zone as the Basque Country [33] (despite lower average temperatures ), such as France or Croatia. In cooler European countries, rising average temperatures lead to lower overall consumption, as slightly higher temperatures do not result in the use of air conditioning.

In other locations, such as the United States, net consumption is projected to rise, given that the increased need for cooling is greater than the decreased need for heating [39]. The extension of air-conditioning devices in the residential sector is much higher in the USA (65%) than in the European Union (5%) [16].

Another relevant remark, from a policy perspective, is the necessity to align climate change mitigation and adaptation policies [40]. As more information on climate change impacts becomes available, long term emission reductions policies should evaluate whether proposed measures are resilient, and their development might be jeopardized by unavoidable climate change.

Several limitations in the data should be noted. Available data on electricity consumption is limited in scope when compared with climate data. Monthly data are limited to the period of 2012-2017 (six years), and as more become available they may be compared with the projections set out in this paper. Similarly, using data with a higher temporal resolution could provide more precise results.

In general, these results will benefit from continued research in the field, and it will be especially important to understand to what extent the expected electrification of heating systems will impact the sensitivity of demand. In any case, it seems that the current and expected proportion of the thermal differential on cold days will continue to be substantially more significant than on warm days, in accordance with the methodology used in the literature.

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## Supplementary Material. Correlation analysis and test of statistical significance.

### Variables used:

| | |
|---|---|
| VAR00001 | Total consumption |
| VAR00002 | Agriculture, forestry and fishing |
| VAR00003 | Extractive industries |
| VAR00004 | Electricity, gas and steam |
| VAR00005 | Food, drink and tobacco |
| VAR00006 | Textile, clothing, leather and footwear |
| VAR00007 | Wood, paper and graphic arts |
| VAR00008 | Rubber and plastics |
| VAR00009 | Chemical, petrochemical and pharma |
| VAR00010 | Metallurgy |
| VAR00011 | Electric equipment, machinery, transportation materials |
| VAR00012 | Construction and public works |
| VAR00013 | Transportation and storage |
| VAR00014 | Hospitality |
| VAR00015 | Commerce and services |
| VAR00016 | Residential |
| VAR00017 | Public service and administration |
| VAR00018 | HDD+CDD |
| VAR00019 | HDD |
| VAR00020 | CDD |

**Results:**

| | | ÁLAVA | | | BISCAY | | | GIPUZKOA | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | HDD+CDD | HDD | CDD | HDD+CDD | HDD | CDD | HDD+CDD | HDD | CDD |
| VAR00001 | Pearson correlation | 0.357563047 | 0.356836368 | 0.042342654 | 0.27843014 | 0.279438456 | -0.204060144 | 0.475517042 | 0.475649665 | -0.180593213 |
| | Significance (two-tailed) | 0.002045441 | 0.002092081 | 0.723968719 | 0.017872595 | 0.017445499 | 0.085551397 | 2.43022E-05 | 2.41578E-05 | 0.128994942 |
| | N | 72 | 72 | 72 | 72 | 72 | 72 | 72 | 72 | 72 |
| VAR00002 | Pearson correlation | -0.702600306 | -0.704124333 | 0.491184479 | -0.141499272 | -0.137727385 | -0.209956857 | -0.097780961 | -0.097720299 | 0.027717682 |
| | Significance (two-tailed) | 6.03959E-12 | 5.19543E-12 | 1.18174E-05 | 0.235770712 | 0.248618932 | 0.076701939 | 0.413849129 | 0.414140258 | 0.817221192 |
| | N | 72 | 72 | 72 | 72 | 72 | 72 | 72 | 72 | 72 |
| VAR00003 | Pearson correlation | -0.084108555 | -0.084630534 | 0.124867002 | -0.424846999 | -0.426145496 | 0.293793315 | -0.119574196 | -0.119147439 | -0.00386593 |
| | Significance (two-tailed) | 0.482404572 | 0.479681199 | 0.295983581 | 0.000199444 | 0.000189734 | 0.012250922 | 0.317088672 | 0.318831418 | 0.974289025 |
| | N | 72 | 72 | 72 | 72 | 72 | 72 | 72 | 72 | 72 |
| VAR00004 | Pearson correlation | 0.047517097 | 0.04722582 | 0.043513216 | 0.110740917 | 0.110058613 | -0.001848269 | -0.066008078 | -0.066956984 | 0.124726324 |
| | Significance (two-tailed) | 0.691836929 | 0.693631957 | 0.71665573 | 0.354407079 | 0.357398244 | 0.987706189 | 0.581704983 | 0.576275596 | 0.296532346 |
| | N | 72 | 72 | 72 | 72 | 72 | 72 | 72 | 72 | 72 |
| VAR00005 | Pearson correlation | -0.469380855 | -0.470637473 | 0.374543823 | -0.28324398 | -0.283215015 | 0.130371054 | -0.584470956 | -0.584602791 | 0.218632976 |
| | Significance (two-tailed) | 3.19277E-05 | 3.0205E-05 | 0.001189686 | 0.015911522 | 0.015922744 | 0.275034943 | 7.03271E-08 | 6.97386E-08 | 0.065025188 |
| | N | 72 | 72 | 72 | 72 | 72 | 72 | 72 | 72 | 72 |
| VAR00006 | Pearson correlation | 0.224554617 | 0.224161651 | 0.014255644 | -0.124059692 | -0.125840691 | 0.188420279 | 0.084876981 | 0.083918427 | 0.072963292 |
| | Significance (two-tailed) | 0.057912808 | 0.058364314 | 0.905392511 | 0.299141829 | 0.292203604 | 0.112954751 | 0.47839824 | 0.483398585 | 0.542463893 |
| | N | 72 | 72 | 72 | 72 | 72 | 72 | 72 | 72 | 72 |
| VAR00007 | Pearson correlation | 0.013704723 | 0.012912398 | 0.150374131 | -0.189449864 | -0.18840387 | 0.012039264 | -0.063935498 | -0.065128164 | 0.150108262 |
| | Significance (two-tailed) | 0.909032839 | 0.91427156 | 0.207374127 | 0.110964673 | 0.11298669 | 0.92004879 | 0.593644354 | 0.586760426 | 0.208187862 |
| | N | 72 | 72 | 72 | 72 | 72 | 72 | 72 | 72 | 72 |
| VAR00008 | Pearson correlation | 0.095780566 | 0.096123022 | -0.093168946 | 0.082409625 | 0.081981385 | -0.007196254 | -0.107994126 | -0.110296983 | 0.284428126 |
| | Significance (two-tailed) | 0.423511732 | 0.421848448 | 0.43631908 | 0.491325213 | 0.493587388 | 0.952160159 | 0.366543116 | 0.356351486 | 0.015458518 |
| | N | 72 | 72 | 72 | 72 | 72 | 72 | 72 | 72 | 72 |
| VAR00009 | Pearson correlation | 0.040680182 | 0.04069704 | -0.014549633 | -0.215077553 | -0.21651092 | 0.205544558 | -0.117519154 | -0.115108547 | -0.217058589 |
| | Significance (two-tailed) | 0.734397239 | 0.734291249 | 0.903450707 | 0.069623716 | 0.067739351 | 0.083251074 | 0.325537086 | 0.335628035 | 0.067030291 |
| | N | 72 | 72 | 72 | 72 | 72 | 72 | 72 | 72 | 72 |
| VAR00010 | Pearson correlation | 0.204611425 | 0.204174599 | 0.02831496 | 0.019349789 | 0.021593824 | -0.173340132 | 0.233637895 | 0.234827635 | -0.209175765 |
| | Significance (two-tailed) | 0.084691307 | 0.085372263 | 0.813352894 | 0.871833546 | 0.857118149 | 0.145352191 | 0.048243601 | 0.047081654 | 0.077830372 |

| | | ÁLAVA | | | BISCAY | | | GIPUZKOA | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | N | 72 | 72 | 72 | 72 | 72 | 72 | 72 | 72 | 72 |
| VAR00011 | Pearson correlation | 0.20717865 | 0.20692924 | -0.00886389 | 0.196685834 | 0.195891794 | -0.033869987 | 0.221641826 | 0.220464219 | 0.048568597 |
| | Significance (two-tailed) | 0.080775778 | 0.081149753 | 0.941091785 | 0.097733072 | 0.099121768 | 0.777600356 | 0.061327941 | 0.062754157 | 0.685371087 |
| | N | 72 | 72 | 72 | 72 | 72 | 72 | 72 | 72 | 72 |
| VAR00012 | Pearson correlation | 0.4060066 | 0.405837357 | -0.079543376 | 0.273586992 | 0.274331742 | -0.182498623 | 0.330473834 | 0.33036215 | -0.103675086 |
| | Significance (two-tailed) | 0.000402412 | 0.000404883 | 0.506569384 | 0.020051123 | 0.019702053 | 0.124939298 | 0.004579515 | 0.004594099 | 0.386131231 |
| | N | 72 | 72 | 72 | 72 | 72 | 72 | 72 | 72 | 72 |
| VAR00013 | Pearson correlation | 0.622703492 | 0.622743482 | -0.180286857 | 0.161249682 | 0.160989881 | -0.056406542 | 0.365285049 | 0.364971995 | -0.094288906 |
| | Significance (two-tailed) | 5.20911E-09 | 5.19399E-09 | 0.129656249 | 0.175999238 | 0.176705875 | 0.637909458 | 0.001604456 | 0.001620518 | 0.430800265 |
| | N | 72 | 72 | 72 | 72 | 72 | 72 | 72 | 72 | 72 |
| VAR00014 | Pearson correlation | -0.331668822 | -0.333075248 | 0.365543794 | -0.400921387 | -0.40008363 | 0.126203524 | -0.675093336 | -0.675715691 | 0.302878264 |
| | Significance (two-tailed) | 0.004426028 | 0.004251238 | 0.00159129 | 0.000482985 | 0.000497589 | 0.290803195 | 7.84258E-11 | 7.42308E-11 | 0.00970747 |
| | N | 72 | 72 | 72 | 72 | 72 | 72 | 72 | 72 | 72 |
| VAR00015 | Pearson correlation | 0.533565347 | 0.533072662 | -0.051945204 | 0.189279588 | 0.189582358 | -0.110704604 | 0.438402647 | 0.436946569 | 0.0025461 |
| | Significance (two-tailed) | 1.39272E-06 | 1.43019E-06 | 0.664761736 | 0.111291916 | 0.110710555 | 0.354565879 | 0.000117266 | 0.000124284 | 0.983065137 |
| | N | 72 | 72 | 72 | 72 | 72 | 72 | 72 | 72 | 72 |
| VAR00016 | Pearson correlation | 0.501124958 | 0.500285026 | 0.024608976 | 0.684598764 | 0.684600593 | -0.320365228 | 0.689951432 | 0.689461561 | -0.188956128 |
| | Significance (two-tailed) | 7.34065E-06 | 7.64642E-06 | 0.83742323 | 3.33737E-11 | 3.33681E-11 | 0.006078336 | 2.03353E-11 | 2.12879E-11 | 0.111915606 |
| | N | 72 | 72 | 72 | 72 | 72 | 72 | 72 | 72 | 72 |
| VAR00017 | Pearson correlation | 0.636807567 | 0.636472336 | -0.111183453 | 0.46284089 | 0.464251345 | -0.319762092 | 0.593133986 | 0.593635222 | -0.261227794 |
| | Significance (two-tailed) | 1.82009E-09 | 1.86731E-09 | 0.352475332 | 4.24639E-05 | 3.99505E-05 | 0.006180078 | 4.01626E-08 | 3.88619E-08 | 0.02666159 |
| | N | 72 | 72 | 72 | 72 | 72 | 72 | 72 | 72 | 72 |

# Conclusions and further research

## 1. Overview

The objective of this thesis has been to contribute to the quantification of how climate change may impact the energy sector. Specifically, impacts on the generation of renewable electricity and demand have been analysed.

As expressed in Chapter 1, this is a young field of research in which most quantitative references are no more than five years old. Everything seems to indicate that the identified impacts will affect the sector's value chain including, among other things, the supply and demand of electricity [1,2].

In the case of supply, renewable generation has received greater attention than conventional generation, as its availability is more closely linked to climate variables [3]. Hydroelectric and wind generation have been the most studied thus far, particularly in Europe, as shown in Chapter 1.

With regards to demand, impacts can occur in multiple sectors and in distinct ways. In the housing sector, as discussed in Chapter 4, a gradual change in temperature can bring both benefits (a reduction in heating on cold days) and costs (an increase in cooling on warm days).

## 2. Impacts on supply

This thesis has dedicated two chapters to the quantitative study of the impacts of climate change on hydroelectric and wind generation in several selected plants (Chapters 2 and 3). In both cases, we have developed methodologies that focus specifically on the impact of climate change, as opposed to the large number of other variables that can also affect both types of generation in the long term. Both chapters take an individual approach to specific plants, as well as the incorporation of economic variables.

Otherwise, the methodologies vary. In both cases we have experimented with several methods and data sets until finding those that best fit the existing data and objectives. In the case of hydroelectric generation, we have worked with a model that simulates the operation of the plants based on technical variables, while for wind plants ex post power curves have been used. These relate active power with wind speed throughout a given reference period.

Chapter 2 has demonstrated the significant impact that changes in rainfall and runoff patterns can have on hydroelectric generation in Spain. Based on public projections from official bodies, an estimate of how individual plants may be affected can be obtained.

In this sense, for example, it has been shown that the existence of a reservoir does not necessarily better prepare a plant for the effects of climate change. However, the size of a plant can be decisive in this regard. This study shows that a plant that uses less existing water may, in turn, be less affected by a decrease in runoff. That is, it reduces watering without substantially reducing production. On the other hand, the load capacity (generation per unit of power) can also be crucial.

In any case, the conclusions are compelling and suggest that the decrease in runoff may have a significant impact on the operating margins and investment parameters of hydroelectric power in Spain and, given the literature shown in Chapter 1, in Southern Europe. This poses a threat not only to the stability of the electricity supply, but also to the mitigation of climate change. It should also be taken into account that the hydroelectric sector operates with investments and concessions in the very long term, and that its adaptability is more limited than other technologies. On the other hand, there may arise conflicts of use with other users, such as the agricultural or residential sectors [4].

In subsequent works not included in this thesis, the authors have analysed plants located in other areas in a mountainous context. Here, the decrease in temperatures and the advancement or disappearance of melting has a decisive effect on the stability of production. In this subsequent study, the authors worked with more current and differentiated projections of CEDEX [5] which were not available at the time of publication of Chapter 2 of this thesis.

Unlike in the case of hydroelectric power, the projected physical changes are not as noticeable for wind energy, which are consistent with the values provided by the literature presented in Chapter 1. However, the analysis shows that various parks may experience economic problems due to regulatory changes and the disappearance of the investment subsidy in Spain. The regulatory framework, in this case, seems to be more relevant than climate change itself, as shown in the text.

At the same time, once again the load capacity (generation per unit of power) gives us a very accurate approximation of profitability for each park. Seasonal changes are also highly relevant and, in the context of differentiated remuneration throughout the year, significantly affect the plants' performance.

The study has not taken in to account possible changes in wind direction. In subsequent works not included in this thesis we have continued our research in this regard, generating different ex post curves for each wind direction. It is an approximation that we have not yet seen in the literature, and which can shed some light on another relevant variable, given that the power curves of the parks can vary substantially depending on wind direction. Our research team is also working on quantifying how changes in temperature may affect air density and the performance of the turbines.

Finally, in other geographical contexts, changes in extreme wind patterns will be highly relevant and may occasionally cause substantial damage to facilities [6].

## 3. Impacts on demand

Chapter 4 examined demand. In this case, the focus is on determining the influence of temperature on electricity demand in the Basque Country. To this end, a methodology frequently seen in the literature is used to quantify the thermal differential of the daily average with respect to certain comfort thresholds (HDD and CDD).

After analysing the demand in different sectors, it can be concluded, logically, that residential demand is the most influenced by meteorology. Here, demand is projected based on expected changes in the evolution of thermal differentials, which indicate that a reduction in future demand is expected. This would also entail a reduction in costs and $CO_2$ emissions.

These conclusions, although initially surprising, are justifiable if differentials on cold days are considered to be substantially greater than those on warm days, due in part to the mild climate of the studied area. The literature is divided on this issue, although most suggest that this may be the general trend in Europe even in Mediterranean countries.

In any case, we must be cautious due the large number of variables that could influence demand in the long term. We have continued working on a more complete framework that integrates other representative social, technical and economic aspects.

## 4. Limitations and future research

As noted in the introduction, determining the impact of climate change in the long term is a difficult challenge and is subject to a large number of variables in a context of uncertainty. Therefore, in the different chapters we have worked to simplify the scope of the reality studied.

Other limitations of the study have to do with the lack of information or resolution. The projections used in Chapter 2 offer a limited resolution, although the results have been contrasted with alternative methods. The series of electricity demand data in Chapter 4, for its part, is limited when compared to the scope and precision of climate data. In addition, due to its monthly periodicity, we have not been able to use other explanatory variables of demand (economic, social or demographic).

These chapters have been completed and published, but we acknowledge its imitations and would like to continue working on unexplored ideas as challenges and potential future lines of research. The literature in this field is still emerging and also follows this path. Some technical limitations in Chapter 3, such as the consideration of changes in wind direction or expanding the resolution of the bins, have been taken into account in subsequent investigations. We continue to work to improve our ability to explain demand.

There are other lines of research that seem relevant. One of them is to quantify how the incorporation of adaptation measures can affect the impacts. The ability to adapt may differ depending on capital needs and the amortization periods of the plants and their infrastructure.

On the other hand, in the case of hydroelectricity, the potential for conflicts of use between the energy sectors and other users of the resource could lead to another line of research, both geographically localized and multisectoral.

Finally, it is important to shed some light on the impacts on less studied technologies, such as solar or bioenergy, which will play a relevant role in the future of generation and may also be affected [7,8].

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# Resumen

El cambio climático se atribuye, entre otras variables, a las emisiones de gases de efecto invernadero producidas por el sector energético. Al mismo tiempo, el cambio climático se espera que pueda afectar a este sector cambiando la disponibilidad de sus recursos, alterando sus condiciones habilitantes y transformando los patrones de la demanda.

Esta tesis aborda los impactos del cambio climático en la generación renovable y en la demanda de electricidad, proporcionando una introducción a las transformaciones más relevantes proyectadas por la literatura y desarrollando metodologías y análisis cuantitativos que determinan el impacto específico en tres casos de estudio.

El primer capítulo ofrece un resumen y análisis de los más relevantes estudios que proporcionan estimaciones cuantitativas de cambio en la generación renovable debido al cambio climático. El segundo y el tercer capítulo se centran en determinar los cambios esperados en la generación hidroeléctrica y eólica en plantas específicas. Ambos proporcionan proyecciones físicas y económicas de los cambios esperados, junto con conclusiones para el desarrollo de políticas energéticas.

El último capítulo profundiza en cómo el cambio climático puede afectar a la demanda de electricidad de una región, debido a los cambios esperados en la temperatura. La tesis se cierra con algunas conclusiones y proporcionando pautas para la investigación futura.

# Abstract

Climate change is atributed, among other factors, to greenhouse gas emissions produced by the energy sector. At the same time, climate change is expected to affect this sector by changing the availability of resources, altering its enabling conditions and transforming demand patterns.

This thesis addresses climate change impacts on renewable generation and electricity demand by providing an overview of the most relevant transformations projected in literature and by developing methodologies and quantitative analysis to ascertain the specific infuence in three case-studies.

The first chapter summarizes and analyzes the most relevant studies that project quantitative changes on renewable generation due to climate change. The second and third chapters focus on estimating climate change impacts in hydropower and wind generation in specific plants. Both provide physical and economic projections of expected changes, along with conclusions for the development of energy policies.

The last chapter delves into how climate change may affect electricity demand due to projected increases in temperature in one region. The thesis ends with some concluding remarks and some insights for future research