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# A systematic review of the impacts of climate variability and change on electricity systems in Europe

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## ABSTRACT

Understanding the impacts of climate variability and change[1] (CV&C) on electricity systems is paramount for operators preparing for weather-related disruptions, policymakers deciding on future directions of energy policies and European decision makers shaping research programs. This study conducted a systematic literature review to collate consistent patterns of impacts of CV&C on electricity systems in Europe. We found that, in the absence of adaptation and for current capacity, thermal electricity generation will decrease for the near term to mid-21st century[2] (NT-MC) and the end of the 21st century[3] (EC). In contrast, renewable electricity generation will increase for hydroelectricity in Northern Europe (NT-MC and EC), for solar electricity in Germany (NT-MC) and the United Kingdom and Spain (NT-MC and EC) and for wind electricity in the Iberian Peninsula (NT-MC) and over the Baltic and Aegean Sea (NT-MC and EC). Although the knowledge frontier in this area has advanced, the evidence available remains patchy. Future assessments should not only address some of the gaps identified but also better contextualise their results against those of earlier assessments. This review could provide a starting point for doing so.

### HIGHLIGHTS

- Systematic reviews are useful for synthesizing climate change research
- Consistent patterns of impacts of CV&C include a decrease in thermal electricity generation across Europe and an increase in renewable electricity generation in parts of Europe in the near term to mid-21st century and the end of the 21st century.
- The results help electricity operators complement their evidence base and prepare for weather-related disruptions, national policymakers to ensure continued provision of critical services and European decision makers to shape future energy policies and research programs.

### KEYWORDS

Climate variability and change (CV&C), Electricity generation and electricity network, Impact assessment, Climate projection, Europe, Systematic review

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[1] CV&C: Climate Variability and Change
[2] NT-MC: Near term to mid-21st century
[3] EC: End of the 21st century

## About the Authors

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He is the recipient of a European Research Council Starting Grant on Advancing Knowledge Systems to Inform Climate Adaptation Decisions – Project ICAD (2012-2016). Suraje is also currently involved in two large European projects: European Provision Of Regional Impact Assessment on a Seasonal-to-decadal timescale (EUPORIAS) and Bottom-up Climate Adaptation Strategies towards a Sustainable Europe (BASE).

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He is leading the CCCEP second phase research theme on enabling rapid transitions in mitigation and adaptation. Jouni has published his research in journals such as Science, Ecology and Society, Ecological Economics and Energy Policy, and have co-edited three volumes published by Blackwell, MIT Press and Routledge. He is also a member of the Scientific Committee of the European Environment Agency (EEA) and editorial boards of Ecological Economics and Environmental Policy and Governance.

## 1- INTRODUCTION

Devastating consequences of extreme weather are repeatedly making the front pages of the media across Europe, as they challenge the provision and security of critical services (e.g. BBC (2015; 2016); Gayle (2015)). Understanding the impacts of climate variability and change (CV&C) on electricity systems[4] is increasingly important not only for electricity companies providing such critical services, but also for policymakers in charge of ensuring the security of a country's electricity supply. As energy infrastructures form the central nervous system of all economies, interruption of electricity provision can have consequences reaching far beyond the electricity systems themselves.

Although the global impacts of CV&C on the energy sector have been explored in the literature (Ebinger and Vergara 2011, Bruckner T., Bashmakov et al. 2014), the impacts of CV&C on the electricity systems have received less attention and regional, national and local assessments are still rare (Chandramowli and Felder 2014).

Existing studies of impacts of CV&C on electricity systems can be divided into three strands. First, some studies use the findings from empirical literature to assess the impacts of CV&C beyond electricity systems. For example, Mideksa and Kallbekken (2010) examine the impacts of CV&C on demand and supply in the electricity markets whilst Rübbelke and Vögele (2011; 2013) investigate the impacts of global warming on trade in electricity between European countries and on national electricity prices. Schaeffer, Szklo et al. (2012) explore the literature on the impacts of CV&C on resource endowments, energy supply, and energy use and infrastructure.

Second, some assessments, such as Klein, Olonscheck et al. (2013), construct indices to assess the susceptibility of the energy sector to the impacts of CV&C: they compare the impacts on energy systems in 21 European countries using an index based on variables such as summer temperature increases, discrepancies between production and consumption and the volume of imports and exports. Bardt, Biebeler et al. (2013) in turn compute risks and opportunities posed by changing climatic conditions for energy sectors in France, Germany, Norway and Poland on the basis of expert interviews.

Third, some assessments focus on the statistical relationships between climatic and energy variables. They use the outputs of climate modelling experiments as inputs in electricity generation and network impact models. Peer-reviewed articles using this approach were the objects of this systematic review. The systematic review approach was used in order to collate, evaluate and interpret all the results of such research.

[4] Electricity systems are defined here as networks of physical assets used for electricity generation, transmission and distribution

This review aims to identify the impacts of CV&C on electricity systems in Europe to answer the questions: i) what patterns of impacts of CV&C on electricity systems can be identified by collating the results of peer-reviewed articles? ii) are any of these patterns robust?

The rest of the article is divided into four sections. Section two describes the method used in the systematic review and the data. Section three presents the results of the systematic review, including robust patterns of impacts of CV&C on electricity systems in Europe. The final two sections discuss the implications of the results for further studies and for decision-making and conclude.

## 2- METHOD AND DATA

### 2.1- Method

The peer-reviewed articles included into this study were selected using a systematic literature review (SLR, see Berrang-Ford, Pearce et al. (2015)). A literature review is "systematic" when it is based on a clearly formulated question, identifies relevant studies, appraises their quality and summarises their evidence (Khan, Kunz et al. 2003). The SLR methodology is explicit and contains enough information to be reproducible. SLRs collate, evaluate and interpret all research available and relevant to a particular question, topic area, or phenomenon of interest. SLRs are widely used in medical research but they are still under-utilised in other disciplines including in climate science (Porter, Dessai et al. 2014).

The well-defined methodology makes SLRs less likely to be biased. SLRs can also provide information about the effects of a phenomenon across a wide range of settings and empirical methods; if the studies yield consistent results, the reported effects can be considered robust. If, on the other hand, the SLR yields inconsistent results, these dissimilarities can be analysed further (Biondi-Zoccai, Lotrionte et al. 2011).

SLRs have also their shortcomings. They are time-sensitive snapshots of the literature on their subject. Another drawback is closely linked to the type of evidence commonly used in SLRs: significant results published in peer-reviewed articles, which leads to under-representation of non-significant results.

The results of the reviewed articles were collated to assess whether robust patterns of impacts of CV&C can be identified at regional, national or sub-national scales on any parts of the electricity systems. The term "robust" does not refer here to "statistical robustness" as is sometimes done in climate science where future changes are considered robust "when i) present-future model ensemble mean difference is significant at the 95 % confidence level according to the Wilcox-Mann–Whitney test applied to the whole model ensemble (adapted from Jacob, Petersen et al. (2014)) and ii) at least 12 models out of 15 agree on the sign of change" (Tobin, Vautard et al. 2015). In this SLR we use Lloyd (2015) definition of robustness as "the standard convergence of predictions/retrodictions of multiple instantiations of variants of the model-type, as well as exploration and empirical confirmation of an array of empirical model assumptions, which can be seen as aspects of random, well-supported experiments when a variety of evidence inferences to support the core structure are used". This is a more qualitative take on robustness, in which the convergence of the results of independent empirical studies corroborates a given phenomenon.

The SLR was carried out in three successive steps: a) search for peer-reviewed articles in Scopus using different keyword combinations; b) screening of the returned articles by applying inclusion and exclusion criteria and a star-rating scorecard, and; c) collation and analysis of the results from the subset of included articles.

Scopus was chosen over Web of Science (WoS) as a search database because it covers four times more journals. The search included records from 1960 (i.e. "all years" in Scopus) to mid-2015 (i.e. 19th of July 2015). When selecting the search keywords, care was taken to use both generic and specific terms (Egan, MacLean et al. 2012) and to include relevant word variants related to climate variability and change and climate data (i.e. climat*, climat* change, climat* project*, climat* model*, climat* condition*, weather, stochastic simulation, change, project*, model*, condition*), impacts and vulnerability (i.e. impact*, ?ffect*, sensitivity, susceptibility, availability, potential*, performance, vulnerab*, assessment, consequence*, *plication) and electricity or power (i.e. energy, power, electric*, hydropower, hydro*, *energy, *lectric*).

First the accuracy of the search strategy was ensured by comparing the returned articles resulting from searches in Scopus to a benchmark collection of relevant studies collated from previous work (Bonjean Stanton, Dessai et al. 2016). Then, 734 searches were run in Scopus using the improved keyword combinations. The searches yielded a total of 24463 articles (including duplicates). Once imported into the EndNote software, the articles were screened using inclusion and exclusion criteria. The retained peer-reviewed articles were in English, with European coverage (as defined by the United Nations Statistics Division), and focussing on the impacts of CV&C on electricity generation and networks in the near-, medium- and long-term.

Following Porter, Dessai et al. (2014), the retained articles were screened using a scorecard to differentiate between rigorous and less rigorous publications. The scorecard's star-rating scheme ranges from zero to five stars. In a five star article the study design and methods are highly appropriate for the research question and they are clearly outlined and justified. Several climate models and scenarios are used for assessing impacts for several time-periods, annually and seasonally. The information on the calibration and validation of the climate and impact models used is explicit. The results are triangulated and set in the context of other studies (e.g. Finger, Heinrich et al. (2012); Majone, Villa et al. (2015); See

Supplementary Material). In a four star article, the methods are clearly justified and several climate models and scenarios are used in the assessment but information on model calibrations, study limitations, or result triangulation is missing. In a three star article, the chosen method is appropriate for the assessment to be carried out. Information on the number and types of climate scenarios and climate and impact models used and their calibration is mentioned but not explained in detail. The results are clearly presented but their implications are not outlined explicitly nor triangulated against other studies. Articles using a single climate scenario, 1-2 climate model(s) and pre-compiled climate variable datasets were also classed as three star articles. Articles scoring less than 3 stars were excluded; such articles provided too little information on the method and the datasets used in the assessment and hence the results of such studies were not considered to be sufficiently rigorous to be included in this review.

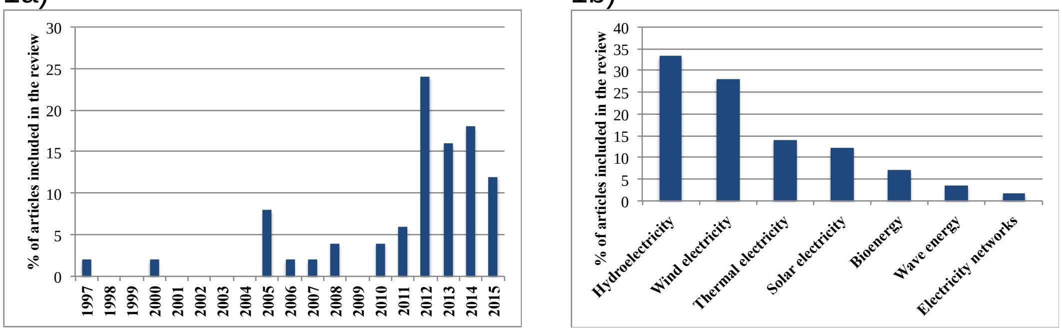
Out of the 50 peer-reviewed articles retained for review, 9 were classed as five star, 29 as four star and 12 as a three star. Using the latest climate models or scenarios (e.g. the Representative Concentration Pathways, RCPs) did not automatically qualify the article as five star; all the scorecard attributes were considered conjointly to assign an article to a star category.

### 2.2- Data

There were 50 articles scoring three stars or more. They were retained for further analysis and labelled #1-50 (See Supplementary Material). Their publication dates range from 1997 to 2015: there are more publications for years 2012 and onwards compared to the earlier years (**Figure 1**). A third of the articles are on hydroelectricity generation, followed by articles on wind electricity (28%), thermal electricity (14%), solar electricity (13%), bioenergy (7%), and wave energy (3%). One article focused on the electricity networks (2%).

**Figure 1:** Retained articles by publication year (1a) and by electricity system focus (1b)

1a) 1b)




Information was collated on the authorship, assessment methods, results, limitations and research gaps of each retained article by using a qualitative record sheet template. In particular, it was discerned: i) what are the projected impacts of CV&C (positive, negative, no significant impact) on the electricity systems for the period of assessment in the articles? and ii) whether these results are in agreement with results of other articles, i.e. can robust patterns be identified from the results?

A total of 43 articles on the impacts of CV&C on hydro-, wind, thermal and solar electricity generation were analysed and the results are reported in the next section. Results from the articles focusing on bioenergy, wave energy and electricity networks (n=7) were not included in the analysis because of the limited and conflicting evidence base they provided but are presented in the Supplementary Material.

The remaining 43 articles had assessment periods chosen for reasons of their own (See Supplementary Material). In some articles, the choice was justified by invoking the electricity infrastructure lifespan, whereas others provided little or no justification for the chosen assessment period. The heterogeneity of used assessment periods made it difficult to gain an overall view of the results. To address this challenge, we re-mapped the articles and their results onto two time periods, near term to mid-21$^{st}$ century and the end of the 21$^{st}$ century. Near term to mid-21$^{st}$ century (NT-MC) covers the period from the present until 2071, while the end of the 21$^{st}$ century (EC) covers the period from 2061 until 2100. There were 22 articles covering near term to mid-21$^{st}$ century and 11 articles covering the end of the 21$^{st}$ century. Both periods were covered by 10 articles.

Each article was scrutinised for its results, and an individual result was chosen as the unit of analysis. A result is “individual” if the article outlines it explicitly and its interpretation is not left to the discretion of the reader. An individual result can be explicitly outlined in a table (e.g. Table 2 in Lehner, Czisch et al. (2005)), a figure (e.g. Figure 4 in Crook, Jones et al. (2011)) or in the text (e.g. Baltas and Karaliolidou (2010)). Some articles have several individual results (e.g. Van Vliet, Vögele et al. (2013)) whereas others only have a single one (e.g. Baltas and Karaliolidou (2010) (See Supplementary Material)).

Individual results from the 43 articles were organised by i) the type of electricity generation (hydro-, wind, thermal and solar electricity generation), ii) geographical coverage (regional, national and sub-national scale) and iii) assessment period (near term to mid-21$^{st}$ century or the end of the 21$^{st}$ century). Each combination could have more than one individual result, one individual result, or no result. A pattern of impacts of CV&C was identified when all relevant individual results were consistent, with the pattern direction of change (positive or negative) reflecting the envelope of individual results. When the individual results were inconsistent, no pattern was attributed. If a single individual result existed, a pattern was attributed only if several climate models or scenarios were used in the generation of the individual result. In total our sample contained 498 individual results.

Some limitations remain in the reported systematic review. We used the UN Statistics Division’s clustering of countries to define European regions (Northern, Western, Eastern and Southern Europe). However, as some articles give limited information on their spatial coverage, the exact match of the results with the UN Statistics Division's clustering of countries cannot be fully guaranteed. Also, some articles cover a long time span including both near term to mid-21st century and the end of the 21st century: this makes it difficult to distinguish which impacts to allocate to which assessment period. Therefore, these individual results were allocated to both assessment periods (e.g. #11: 2010-2080; #29: 2020-2080; #30: 1990 – 2080/2100). Articles on the same type of electricity generation were collated regardless of some differences in addressed generation technology and infrastructure. For example, articles on hydroelectricity generation included impact assessments for run-of-the-river and storage reservoir plants, and articles on thermal electricity generation examined generation from fossil fuels and nuclear fuels. The statistical significance of individual results was indicated in some articles but not in others; individual results with no mention of their statistical significance were still included, but non-significant results were not when explicitly characterised as such. Finally, all the reviewed articles are in English, disregarding results reported in other languages. Funding information, where available, revealed that the European Commission, national research councils and ministries, and academic institutions (e.g. university research departments) financed most of the studies, with the exception of one study (#29), commissioned directly by a national energy association.

## 3- RESULTS

### 3.1- Landscape of methods of analysis

The reviewed articles use quite different methods of analysis. The simplest ones take climate data as proxy for the impacts of CV&C (e.g. # 10), whereas more complex ones use outputs of climate model experiments as inputs to comprehensive impact models (e.g. #27).

The climate data used in the assessments can be taken directly from existing climate change projection datasets (e.g. UKCP09 in #6) or be simulated by a) combining emissions scenario(s) and climate model(s)/projection(s) (e.g. #2, #13, #27, #43) or b) by rearranging observed time series with respect to a given linear trend for a selected variable (e.g. STARS[5] in #24). The statistical measures of climate data (e.g. mean, median, distribution) used as inputs to the impact models, also vary.

The impact models used in the articles vary from validated and widely accepted models (e.g. IHACRES[6]) to models specifically developed for the articles and conveyed by a single equation or more complex computations. Impact models also tend to reflect the dominant impact pathway.

[5] STARS or STatistical Analogue Resampling Scheme (From: https://www.pik-potsdam.de/research/climate-impacts-and-vulnerabilities/models/stars [Accessed 09/02/2016])
[6] IHACRES or Identification of unit Hydrographs And Component flows from Rainfall, Evaporation and Streamflow data (From: http://www.toolkit.net.au/tools/IHACRES [Accessed 07/12/2015])

Hydroelectricity generation depends directly on the hydrological cycle. CV&C affect hydroelectricity generation through the availability of excess water (precipitation minus evapotranspiration) and the seasonal pattern of the hydrological cycle in regions where snowmelt is a relevant factor for generation (Schaeffer, Szklo et al. 2012). The impacts of CV&C on hydroelectricity generation are assessed using hydrological models (e.g. rainfall-runoff models such as IHACRES, TOPKAPI[7] or HBV Model[8], GEOTRANSF[9]) or models simulating hydroelectric power plant operations.

Energy contained in wind is proportional to the cube of the wind speed (Pryor and Barthelmie 2010) and thus variations in wind speed can have significant effects on generation. Schaeffer, Szklo et al. (2012) indicate that wind speed varies significantly with height and that little is known about likely future wind speeds at the hub height of a wind turbine (above 50 m). In the reviewed articles, the impacts of CV&C on wind electricity generation is assessed either by taking future wind projections (e.g. GCM geostrophic wind) as proxy for wind power production, or by extrapolating wind speed for the specific height of the hub of the analysed wind turbine model.

Thermal electricity generation using coal, natural gas, nuclear isotopes, geothermal energy and biomass depends on the availability and temperature of cooling water. Its efficiency depends on the heating and cooling needs of both Rankine and Brayton cycles, which in turn vary according to the average ambient conditions such as temperature, pressure, humidity and water availability (Schaeffer, Szklo et al. 2012). Reliability of supply can also be threatened by water abstraction and regulations on discharge water temperature (Naughton, Darton et al. 2012). Water use models (e.g. WaterGAP3[10]), eco-hydrological models (e.g. SWIM[11]), hydrological models and specific models of thermal electricity generation were all used.

Solar electricity generation can be impacted by extreme weather events, changes in snow and cloud cover and air temperature increases. Changes in air temperature not only modify photovoltaic (PV) cell's efficiency and reduce generation (Pašičko, Branković et al. 2012), but also negatively affect temperature-sensitive Concentrated Solar Power (CSP) systems. The impacts of CV&C on solar electricity generation are assessed by using the delta change method, assessing the differences between simulated current and future climate conditions, by developing models of PV power generation, or by deriving the power output from irradiance and ambient temperature data.

Some of the reviewed articles explain the rationale for the choice of the assessment period(s) and used climate and impact models but most do not.

[7] TOPKAPI or TOPographic Kinematic APproximation and Integration (From: http://www.progea.net/prodotti.php?p=TOPKAPI&lin=inglese [Accessed: 07/12/2015])
[8] HBV Model (From: http://www.geo.uzh.ch/en/units/h2k/services/hbv-model/ [Accessed 07/12/2015])
[9] Majone, B., A. Bertagnoli, A. Bellin and A. Rinaldo (2005). GEOTRANSF: a continuous non-linear hydrological model. AGU Fall Meeting Abstracts.
[10] Water Global Assessment and Prognosis or WaterGAP (Eisner, S. and M. Flörke (2015). Benchmarking the WaterGAP3 global hydrology model in reproducing streamflow characteristics. EGU General Assembly Conference Abstracts.
[11] SWIM model or Soil and Water Integrated Model (From: https://www.pik-potsdam.de/research/climate-impacts-and-vulnerabilities/models/swim [Accessed 07/12/2015])

Many articles develop their own methods of analysis, combining a unique set of climate data and impact models. Most articles (with the exception of e.g. Hoffmann, Häfele et al. (2013)) also assess the impacts of CV&C on the basis of climate signals only, and neglect to consider feasible adaptation measures or future change in policies and regulations. Impact models developed in some of the reviewed articles are based on the existing types of electricity infrastructure, designed on the basis of historical meteorological records and not future climate projections. The articles also assume that no new electricity infrastructure will be built and that generation capacity will remain constant. Moreover, all but a few articles consider only one technology for a given type of electricity generation. Lehner, Czisch et al. (2005) do consider both run-off-the-river and reservoir solutions for hydroelectricity generation, Crook, Jones et al. (2011) include in their analysis the two most widely installed solar technologies for large-scale electricity generation, namely photovoltaic (PV) and concentrated solar power (CSP)) and Van Vliet, Vögele et al. (2013) assess different types of thermal electricity generation plants. As a consequence, the methods of analysis were not examined further in the analysis.

## 3.2- Consistent patterns of impacts of CV&C

This section explains the consistent patterns of impacts of CV&C on hydro-, wind, thermal and solar electricity generation at the regional and national scales. The robustness of the patterns of impacts of CV&C is indicated for the regional and national scales, for which there were more often more than one individual result available (*in bracket and in italic; NT-MC: near term to mid-21$^{st}$ century and EC: end of the 21$^{st}$ century*). We use the number of available and consistent individual results as a proxy for robustness; a pattern of impacts of CV&C identified from four or more individual results is considered more robust that one derived from a single result. Robustness is not considered at the sub-national scale because only single individual results were available at this scale.
At sub-national scale, impacts were mostly derived from one individual results per location, not allowing for any pattern to be extrapolated. As such, sub-national scale impacts of CV&C are only discussed in the Supplementary Material.

### *3.2.1- Consistent patterns of impacts of CV&C on hydro-, wind, thermal and solar electricity generation at regional scales*

Figure 2 summarises the annual consistent patterns of CV&C on hydro-, wind, thermal and solar electricity generation at regional scales. Positive patterns can be observed for renewable electricity generation in Northern Europe and negative patterns for both renewables and traditional electricity generation for the Western, Eastern and Southern Europe.

<u>Hydroelectricity generation</u>

Hydroelectricity generation from the installed hydropower capacity is expected to drop from 10% of the EU27 electricity generation in 2013 to less than 6% by 2050 as the result of future changes in rainfall (#12).

Hydroelectricity generation will increase in Northern Europe (*2 individual results available for NT-MC and 1 for EC*) and decrease in Western (NT-MC*: 1; EC: 1*) and Southern Europe (NT-MC*: 2; EC: 2*) by near term to mid-21$^{st}$ century and by the end of the 21$^{st}$ century. In Eastern Europe, hydroelectricity generation will decrease in the near term to mid-21$^{st}$ century (*1*).

Hydroelectricity generation is projected to increase in winter in Northern Europe (*1*) and decrease in summer for Southern Europe (*1*) for the end of the 21$^{st}$ century.

Wind electricity generation

No consistent patterns of impacts of CV&C on wind electricity generation are projected for Northern Europe for the near term to mid-21$^{st}$ century (*3*). For Northern Europe, an annual increase (*3*) and an increase for the winter months (*1*), and a decrease for the summer months (*1*), are predicted for the end of the 21$^{st}$ century. For Southern Europe, wind electricity generation is predicted to decrease in the near term to mid-21$^{st}$ century and for the end of the 21$^{st}$ century (*NT-MC: 1; EC: 2*). A decrease in generation is also predicted for summers in Western Europe (*1*) and summers (*1*) and winters (*1*) in Southern Europe for the end of the 21$^{st}$ century. The decrease for Southern Europe is consistent with a decrease in annual wind electricity generation in the Mediterranean Sea for the near term to mid-21$^{st}$ century and the end of the 21$^{st}$ century (*NT-MC: 2; EC: 2*).

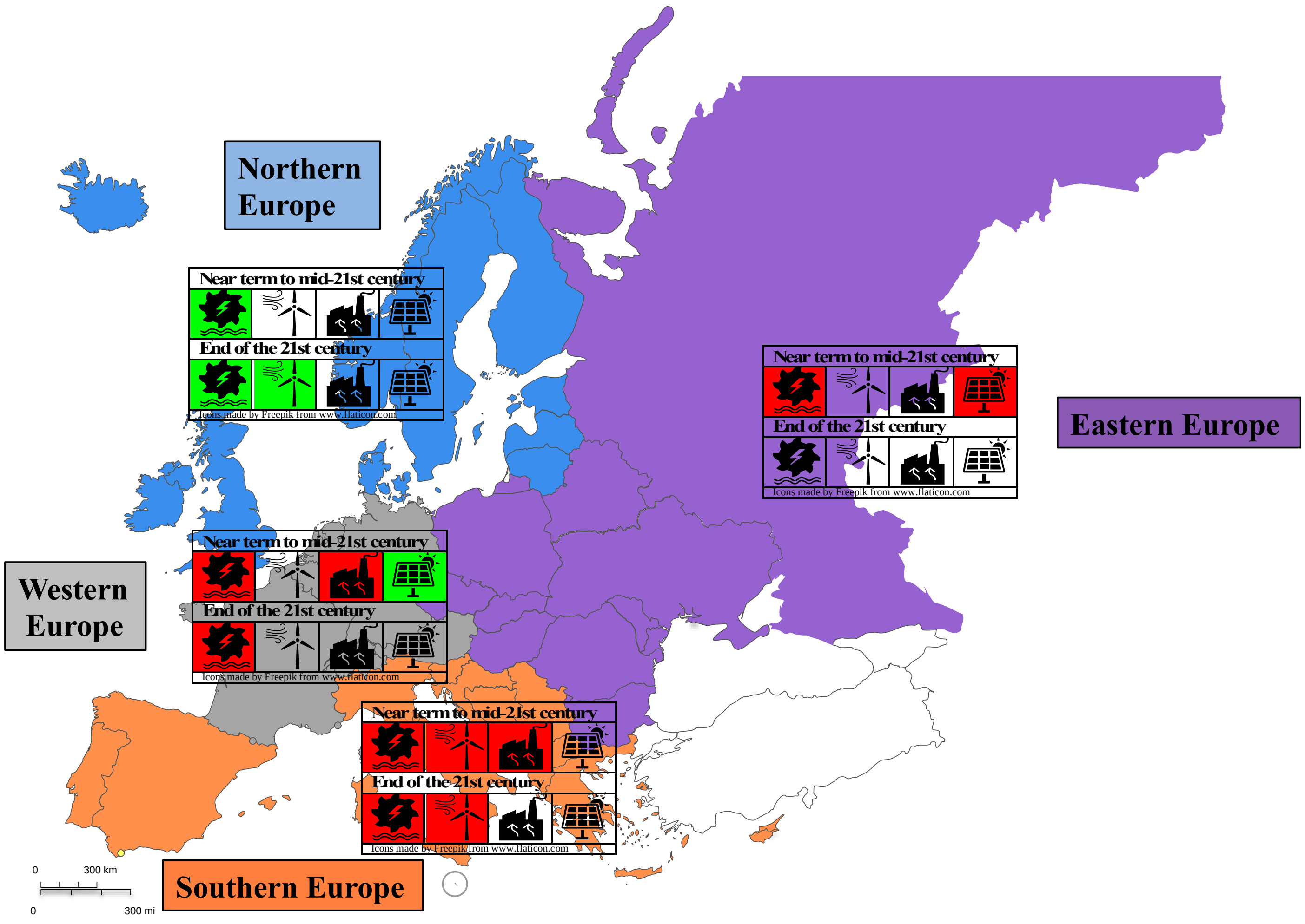
Thermal electricity

Annual thermal electricity generation is projected to decrease in Western Europe (*1*) and Southern Europe for the near term to mid-21$^{st}$ century (*2*). This projection resonates with the projections for decreasing precipitation for Southern Europe (Kovats, Valentini et al. 2014), reducing the volume of runoff available for use as cooling water.

Solar electricity generation

Annual solar electricity generation is projected to increase in Western Europe (*1*) and to decrease in Eastern Europe for the near term to mid-21$^{st}$ century (*1*).

**Figure 2:** Annual consistent patterns of impacts of CV&C on hydro, wind, thermo and solar electricity across the four European regions



### *3.2.2- Patterns of impacts of CV&C on hydro-, wind, thermal and solar electricity generation at national scale*

**Figures 3** and **4** present the annual patterns of impacts of CV&C on hydro-, wind, thermal and solar electricity generation at the national scale and in the Baltic and Mediterranean seas and Iberian Peninsula for the near term to mid-21$^{st}$ century and the end of the 21$^{st}$ century, respectively. The figures also indicate where no pattern could be identified.

**Figures 3** and **4** indicate that national scale assessments of impacts of CV&C are still largely missing for wind, thermal and solar energy generation for the near term to mid-21$^{st}$ century and the end of the 21$^{st}$ century. More individual results are available for the near term to mid-21$^{st}$ century than for the end of the 21$^{st}$ century. There is more agreement between individual results for the end of the 21$^{st}$ century than for the near term to mid-21$^{st}$ century, resulting in more consistent patterns of impacts of CV&C for the later period. This is consistent with stronger climate signals towards the end of the century.

**Figure 3**: Annual patterns of impacts of CV&C on hydro-, wind, thermal and solar electricity generation at national scale for the near term to mid-21st century

*(Sources: Hydroelectricity: #25 (1 individual result), #26 (72), #34 (1), #35 (1), #43, (1) and #47 (70); Wind energy: #3(3), #44(2); Thermal electricity: #22(12), #24(1); Solar energy: #6(3), #11(8))*

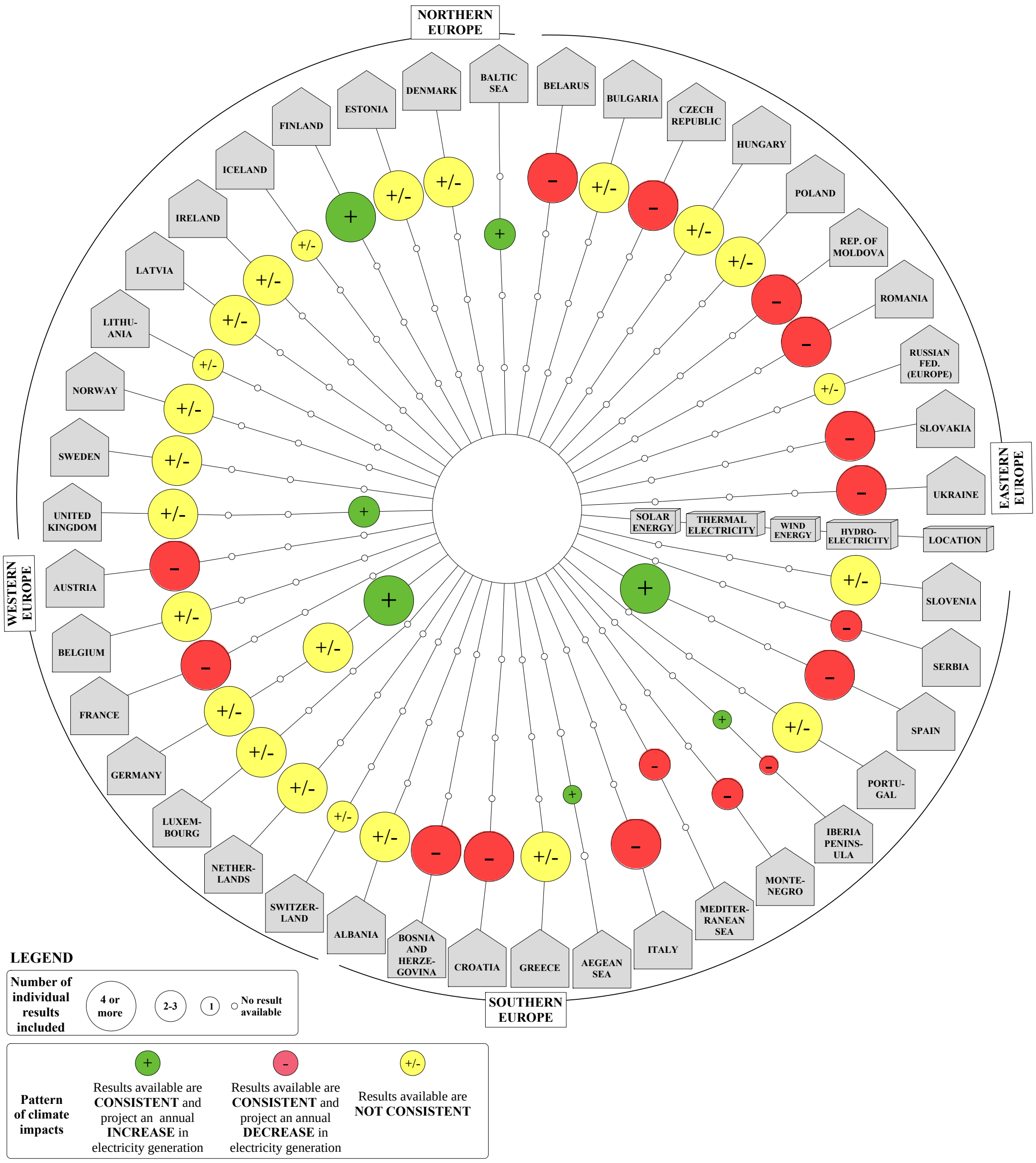
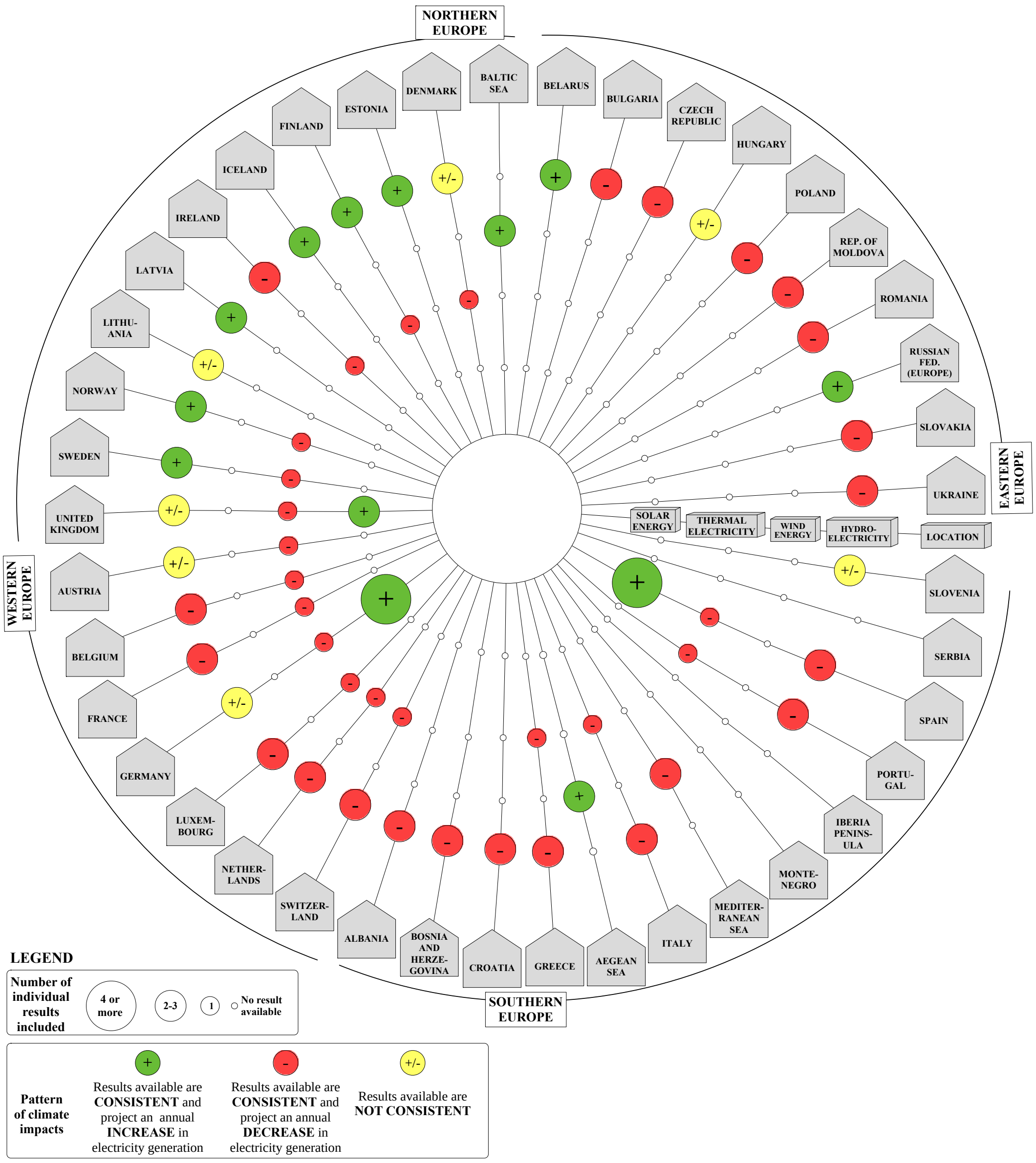


**Figure 4**: Annual patterns of impacts of CV&C on hydro-, wind, thermal and solar electricity generation at national scale in the end of the 21st century
*(Sources: Hydroelectricity: #17(16 individual results), #26 (72); Wind energy: #5(1), #23(1), #36(1), #44(3); Thermal electricity: #17(16); Solar energy: #6(3), #11(8))*



Hydroelectricity generation

Finland is the only country with a confirmed positive pattern of increased hydroelectricity generation for the near term to mid-21st century (*4*). Northern European countries of Estonia (*2*), Finland (*3*), Iceland (*2*), Latvia (*2*), Norway (*3*) and Sweden (*3*) and Belarus (*2*), and the European part of the Russian Federation (*2*) in Eastern Europe, are also projected to experience an increase in hydroelectricity generation in the end of the 21st century.

Consistent negative patterns of impacts of CV&C on hydroelectricity generation exist for Austria (*4*) and France (*4*) in Western Europe, for Belarus (*4*), Czech Republic (*4*), Moldova (*4*), Romania (*4*), Slovakia (*4*) and Ukraine (*4*) in Eastern Europe and for most countries in Southern Europe (Bosnia-Herzegovina (*4*), Croatia (*5*), Iberian peninsula (*1*), Italy (*4*), Montenegro (*2*), Serbia (*2*) and Spain (*4*)) for the near term to mid-21st century. For the end of the 21st century, hydroelectricity generation is projected to decrease for Ireland (*3*), and for most Western European countries (Belgium (*3*), France (*3*), Luxembourg (*2*), Netherlands (*3*), Switzerland (*3*)), for Eastern Europe (Bulgaria (*2*), Czech Republic (*2*), Poland (*2*), Moldova (*2*), Romania (*2*), Slovakia (*2*) and Ukraine (*2*)) and for Southern Europe (Albania (*2*), Bosnia-Herzegovina (*2*), Croatia (*2*), Greece (*3*), Italy (*3*), Portugal (*3*), Spain (*3*)).

Wind electricity generation

There is substantial uncertainty associated with assessing projected changes in wind (Pryor, Barthelmie et al. 2005). Despite this, reviewed articles indicate some patterns. An increase in annual wind electricity generation is projected for the Baltic and the Aegean Seas for the near term to mid-21st century and the end of the 21st century (*respectively for the NT-MC: 2, 1; EC: 2, 3*) and for the Iberian Peninsula (*1*) for the near term to mid-21st century. An annual decrease is projected for the Mediterranean Sea for the near term to mid-21st century and the end of the 21st century (*NT-MC: 2; EC: 2*).

Wind electricity generation is projected to increase in summers for the Baltic and Aegean Seas (respectively: *1* and *1*) and in winters (November to February) for Germany (*1*) and Ireland (*2*) in the near term to mid-21st century, and for the United Kingdom (*1*) for the end of the 21st century.

A decrease in wind electricity generation is projected for summers for Ireland (*2*) and Germany (*1*) in the near term to mid-21st century, and for France (*1*), the United Kingdom (*2*), Germany (*2*) and Poland (*1*) for the end of the 21st century. A decrease is projected for springs and autumns for the Iberian Peninsula for the end of the 21st century (*2*).

Thermal electricity generation

Thermal electricity generation is projected to decrease for the near term to mid-21st century and the end of the 21st century across Europe. For near term to mid-21st century Germany, thermal power plants with once-through cooling (OTC) systems are consistently projected to experience a decrease in generation (*7*) but no consistent pattern of impacts can be identified for power plants with closed-circuit cooling (CCC) systems (*6*). All individual results project annual decrease in thermal electricity generation for the end of the 21$^{st}$ century (Denmark (*1*), Finland (*1*), Ireland (*1*), Norway (*1*), Sweden (*1*), United Kingdom (*1*), Austria (*1*), Belgium (*1*), France (*1*), Germany (*1*), Luxembourg (*1*), Netherlands (*1*), Switzerland (*1*), Greece (*1*), Italy (*1*), Portugal (*1*) and Spain (*1*)).

<u>Solar electricity generation</u>

Annual solar electricity generation is projected to increase for the United Kingdom, Germany and Spain for the near term to mid-21$^{st}$ century (*(3)*, *(4)*, *(4)*), and for the end of the 21$^{st}$ century (*(3)*, *(4)*, *(4)*).

## 4- DISCUSSION

Robust negative patterns of impacts of CV&C were identified for thermal electricity generation for the near term to mid-21$^{st}$ century and the end of the 21$^{st}$ century. In contrast, positive patterns were identified for renewable electricity generation; robust positive patterns of impacts of CV&C can be found from the projections for increased generation of hydroelectricity in most of Northern Europe in the near term to mid-21$^{st}$ century and end of the 21$^{st}$ century, for solar electricity in Germany in the near term to mid-21$^{st}$ century and in the United Kingdom and Spain in the near term to mid-21$^{st}$ century and end of the 21$^{st}$ century, and for wind electricity in the Iberian Peninsula in the near term to mid-21$^{st}$ century and over the Baltic and Aegean Sea in the near term to mid-21$^{st}$ century and end of the 21$^{st}$ century.

Future climate projections are in agreement about an increase in temperature throughout Europe, and about increasing precipitation in Northern Europe and decreasing precipitation in Southern Europe (Jacob, Petersen et al. 2014). Episodes of high temperature extremes are also expected to become more frequent (high confidence) and so are meteorological droughts (medium confidence) and heavy precipitation events (high confidence) (Kovats, Valentini et al. 2014). These climatic projections resonate with the patterns of impacts of CV&C on electricity systems identified in this systematic review. Increased ambient air temperatures will decrease the efficiency of thermal generating plants and reduce thermal electricity generation across Europe. Higher precipitation will be favourable to hydroelectricity generation in Northern Europe, but decreasing precipitation will reduce hydroelectricity generation in Southern Europe (**Figures 3** and **4**).

The results of this review also highlight further the vulnerability to CV&C of more traditional electricity generation technologies such as thermal power plants. The key issue in managing such assets in the face of future changes is that the past can no longer be assumed to be the best guide for the future. As such infrastructure managers should not rely only on past conditions but also consider a range of future scenarios. They should also envisage potential adaptation options for not only climate-proofing traditional technologies but also diversify their electricity generation asset portfolio and encourage the penetration in the energy mix of less climate vulnerable electricity generation technologies such as renewables. Transitioning towards more renewable sources of electricity could also simultaneously support the achievement of the European Union's commitment to reduce GHG emissions from 1990 levels by 40% by 2030 and by 80-95% by 2050, to retain global warming below 2ºC (European Commission 2011). It would also help achieving the binding EU target of covering at least 27% of the European energy consumption from renewable sources by 2030 (European Commission 2014).

A systematic review of the assessments of impacts of CV&C on electricity systems makes several contributions. First, validation and invalidation of specific results can lower uncertainty and remove barriers from decision-making. Second, as most individual results are not directly transferable to other locations (e.g. Gaudard, Romerio et al. (2014)) or attributable to other electricity infrastructure assets, a systematic review can help to assemble the puzzle of the future impacts of CV&C on electricity systems. Finally, the envelopes of results represent versions of possible futures that policymakers and electricity operators will have to prepare for. They can inform policymakers' plans for a future energy mix capable of withstanding the impacts of CV&C, and interruptions related to them, to ensure the reliability and security of electricity provision. Electricity operators can use such evidence to re-think future investments in electricity generation infrastructure, especially those with long-term lifespan such as hydroelectric dams, and thus limiting the risks of stranded assets. Electricity companies, carrying out their own CV&C risk assessments can also use such evidence to triangulate and reinforce their own findings.

This systematic review identified robust patterns of impacts of CV&C from peer-reviewed articles published in English. Although the knowledge frontier in this area has advanced, the evidence available is still sparse. Little robust assessments still exist on thermal generation (combustible fuel and nuclear power plants) for the near term to mid-21st century and the end of the 21st century. As thermal electricity is the main source of electricity in Europe at present[12] and is likely to remain very prominent in the future electricity mix, understanding more consistently the impacts of CV&C on thermal power plants is paramount to better plan for energy security in the future. Some articles also explored the impacts of CV&C on renewable electricity but to the authors' knowledge no study exists looking more holistically at the potential for future renewable installation capacity at European or national levels and at the effects of renewable penetration on future electricity systems. Additionally, most existing articles assess near term to mid-21$^{st}$ century impacts and fewer articles cover end of the 21$^{st}$ century impacts (**Figures 3** and **4**). Even fewer articles consider intra-annual or seasonal variations. The spatial coverage of assessments is also uneven. Few assessments focus on the impacts of CV&C at national scale on thermal, wind electricity and solar electricity

[12] From: http://ec.europa.eu/eurostat/statistics-explained/index.php/Electricity_production,_consumption_and_market_overview#Electricity_generation [Accessed 15/02/2016]

generation. Sub-national and infrastructure scale assessments are also largely missing, yet they would be key in supporting decision-making. Furthermore, many articles have quite static approach; climate parameters are often the only variables and the energy mix, the commissioning and decommissioning of assets, and the technical parameters for electricity generation are considered constant. Technology innovation is not taken into consideration and nor are future technologies with increased energy efficiencies.

There are inherent cascading uncertainties associated with the climate and impact models used in the assessments, and yet these uncertainties are rarely discussed explicitly in the reviewed articles. There is also little reflection on what the implications of these uncertainties are in practice and how confident the readers and users can be in the results. Future assessments of impacts of CV&C on electricity systems should tailor the communication of results and uncertainties associated with them to specific audiences. Latest literature on communicating climate science would help to better understand the target audiences' needs and preferences, and to tailor the communication of results accordingly (e.g. EU FP7 Euporias[13]). Furthermore, future assessments should communicate uncertainties and confidence in the results more explicitly (Lorenz, Dessai et al. 2013). For example, the latest IPCC AR5 report uses two metrics for communicating the degree of certainty in key findings: confidence in the validity of a finding, based on the type, amount, quality and consistency of evidence and a quantified measure of uncertainty in a finding expressed probabilistically (Intergovernmental Panel on Climate Change (IPCC) 2014).

The articles should also be more explicit about their limitations and outline if possible what the implications of their results are for the stakeholders. For example, few of the reviewed assessments reflect on how to adapt the electricity systems to the impacts of CV&C found in their results.

Assessments of impacts of CV&C on electricity systems often assess the impacts of a single climate variable (a proxy for climate change) on one type of electricity generation or infrastructure asset. To the authors' knowledge, no article has yet looked at the impacts of a climate variable along the whole chain of electricity provision (e.g. the impact of decreasing rainfall on electricity generation and network infrastructure) or investigated the impacts of concomitant weather events on one type of electricity generating technology (e.g. the simultaneous impact of a massive earthquake and a tsunami like in Fukushima in Japan in 2011). Little is also still known about the impacts of CV&C on sector interdependencies. For example, reduced rainfall could lead to droughts, which in turn could translate into not only decreased thermal electricity and hydroelectricity but also into bans and levies on water extraction for irrigation or human consumption. Finally, another area of importance for future modelling is adaptation. Adaptation options should be included in future assessments of impacts of CV&C on electricity infrastructure and the technological and economical efficacy of such option

[13] From: http://www.euporias.eu/ [Accessed 09/10/2015]

evaluated for different climate scenarios. Such studies could be invaluable to help infrastructure managers to climate-proof their assets, to ensure national electricity security and to avoid potential maladaptation.

## 5- CONCLUSION

This systematic review is the first attempt at collating the impacts of CV&C on electricity systems in Europe from peer-reviewed literature published in English. The review indicates that although the evidence base is improving and yields some robust patterns, there is still a need for additional empirical research.

In future assessments there is a need to better contextualise the results against those of earlier assessments. This review can provide a starting point for doing so. Future assessments should also link their results and their implications to user needs and consider how the results are best communicated. Few attempts have been made to date to integrate the assessments of impacts of CV&C on supply and demand of electricity (e.g. Chandramowli and Felder (2014); Ciscar and Dowling (2014)). Such could be the next step in assessment of risks CV&C pose for electricity systems.

This review identified some consistent patterns of CV&C impacts on electricity systems in Europe. As the climate is changing so should energy infrastructure management, policies and the future directions of research. This work could inform not only infrastructure managers trying to climate-proof their assets and avoid resource misallocation but also policymakers shaping future European Energy policies and the European Commission when shaping the future research and funding programs.

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## SUPPLEMENTARY MATERIAL

List of Appendices:

Appendix A- Detailed method followed in the systematic review

Appendix B- Data: Peer-reviewed articles included in the systematic review and their characteristics

Appendix C- Peer-reviewed articles included in the systematic review but excluded from the analysis

Appendix D- Impacts of Climate Variability and Change (CV&C) on hydro-, wind, thermal and solar electricity generation at sub-national scale

## Appendix A- Detailed method followed in the systematic review

The systematic review was carried out in three steps as illustrated in **Figure 5**.

**Figure 5**: The four-step process followed to carry out the systematic literature review

**Step 1: Scopus keyword searches**
**734 searches** using **29 keywords**

Number total of hints returned, i.e. articles for consideration, (**n= 24463**, including duplicates)

**Step 2a: High level screening of the hints returned using inclusion criteria:**
- Content relevant for Europe / Assessment made for a European country or region (as defined by the United Nations Statistics Division )
- In peer-reviewed journals
- In English (both Abstract ad Full Text)
- Paper focusing on climate impacts on electricity generation and transmission in the near, medium and to long-term futures

**Step 2b: Further screening of the remaining results, using a scorecard, assigning the paper to a "star category" based on study design, method used and result presentation**

Rejected (n= 24413)

- Duplicate articles (where results of the same research was published in two or more journals)
- Impact assessment using historical data only (reanalysis deriving future trends from historical trends were included)
- Reviews of existing literature
- Studies on a) potential future energy mix; b) climate change impacts on national energy systems (matching generation and demand but with no detailed info on both); c) Cost Benefit Analysis of renewable energy or green electricity; d) Energy efficiency / performance studies in buildings/ building energy performance etc...e) Energy generation technology feasibility, improvement or performance & determination of suitable areas for implementation; f) Energy markets and prices / Economic impacts of CC on energy sector / Impact of CC on electricity exchange between countries; g) Energy studies in residential or urban areas / cities; h) Energy technology acceptability and diffusion; i) energy use/ demand/ consumption/heating/cooling/conservation; j) energy studies on synergy adaptation and mitigation; k) Energy technology & reduction of GHGs – mitigation; l) environmental and climate & social & economics impacts of the electricity generation technology; m) fracking; n) impacts of non climatic hazards on energy technology / energy generation; o) implementation of climate change policies / policy instruments on energy / impacts of energy policies; p) Modeling or estimating power availability / output; q) past extreme weather events impact management / adaptation; r) power disruption, power reliability, power stability or power availability; s) weather and climate impacts on non generation or transmission aspects of energy technology
- Non relevant / Other thematic area than energy (e.g. Earth's energy flows, Ecosystems energy budgets, meteorology, social& economic consequences of power failure, study on space weather effects, geophysics, molecular biology, meteorology, transport, ecology)

**Step 3: Analysis of the n=50 articles that were included in the review**

*Step 1: Scopus keyword combination searches*

*The keywords used*

**Table 1** presents the keywords that were combined for the searches.

**Table 1**: List of keywords used in the search

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Level 1 | climat* | climat* change | climat* project* | climat* model * | climat* condit-ion* | weather | stochastic simulation | change | project* | model* | condition* |
| Level 2 | impact* | ?ffect* | sensiti-vity | suscept-ibility | availa-bility | potential * | performance | vulnerab* | assessment | conse-quence* | *plication |
| Level 3 | energy | power | electric* | hydro-power | hydro* | *energy | *lectric* | | | | |

*The search process*

Each search was carried out using the following combination of keywords: “One keyword word from Level 1 AND One keyword from Level 2 AND One keyword from Level 3”.

Several combinations of keywords were tested. Results with search terms x and y returned few relevant articles. The relevant articles returned were already covered by other search terms combination

This led to 734 search combinations returning 24463 resources (including duplicates).

*Step 2: High level screening of the articles returned for each of the keyword combination search*

The articles returned for each keyword combination search were screened and only retained if they met all of the following inclusion criteria:
- Content relevant for Europe / Assessment made for a European country or region (as defined by the United Nations Statistics Division[14])
- In peer-reviewed journals
- In English (both Abstract ad Full Text)
- Articles focusing on impacts of climate variability and change (CV&C) on electricity generation and transmission in the xxx

Note: studies on energy resource endorsement were excluded (e.g. impacts of CV&C on coal mining when coal is used as a fuel for thermal electricity generation)

*Step 3: Screening using a star-rating scorecard*

The remaining articles were then further assessed using the star-rating scorecard outlined in **Table 2**. A 5* paper is a paper that includes all the individual attributes outlined in the scorecard.

[14] http://unstats.un.org/unsd/methods/m49/m49regin.htm#europe [Accessed 09/10/2015])

A 4* paper includes the following: D1 (and maybe D2), M1 and at least 4 attributes amongst M2-M9, R1, R2 and at least 2 of the attributes amongst R3-R6.
A 3* paper includes the following: D1 (and maybe D2), M1 and less than 4 attributes amongst M2-M9, R1, R2 and less than 2 of the attributes amongst R3-R6.
Papers scoring below 3* were not retained in the study.

Only fifty articles in total were retained in this study as a result of the systematic review. Their full references can be found in **Table 3** in Appendix B.

**Table 2**: The screening scorecard

| | |
|---|---|
| **Study design** | |
| D1 | The study design is appropriate for the assessment. E.g. appropriate for the scale of the assessment, technology etc. |
| D2 | There is a good balance in the paper between the methods and the results section (some paper have a lot of info on assessment method but the result section is rather underdeveloped even if the key messages are there OR the paper described the model used in details in another paper and concentrates on the results) |
| **Methods** | |
| M1 | The method used for the assessment, etc is outlined |
| M2 | The method used for the assessment, etc is clearly outlined. The information given about the assessment method are enough to allow the study to be reproduced for a different location |
| M3 | The method clearly explains why one climate model, impact model, region of assessment was chosen over another) |
| M4 | The method uses several climate models to create an envelope of climate data / uses ensembles of climate data<br>References:<br>- "Ensemble means have proven to be more accurate than individual models in reproducing the instrumental observational period" (From: Gleckler, P.J., Taylor, K.E., Doutriaux, C., 2008. Performance metrics for climate models. Journal of Geophysical Research: Atmospheres 113, n/a-n/a.)<br>- "In most cases the multi-model mean agrees more favourably with observations than any individual model." (From: Intergovernmental Panel on Climate Change (IPCC), 2014. Climate Change 2013 - The Physical Science Basis: Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental<br>Panel on Climate Change. Cambridge University Press, , Cambridge, United Kingdom and New York, NY, USA(Intergovernmental Panel on Climate Change (IPCC) 2014), p. 767) |
| M5 | The method uses several climate scenarios to forecast different future conditions |
| M6 | The method assesses the impact in the near term to mid-21st century and the end of the 21st century |
| M7 | "The information on the calibration and validation of the climate and impact model used is explicit<br>The climate models were rigorously tested before they are applied<br>Reference:<br>Refsgaard, J.C., Madsen, H., Andréassian, V., Arnbjerg-Nielsen, K., Davidson, T.A., Drews, M., Hamilton, D.P., Jeppesen, E., Kjellström, E., Olesen, J.E., Sonnenborg, T.O., Trolle, D., Willems, P., Christensen, J.H., 2014. A framework for testing the ability of models to project climate change and its impacts. Climatic Change 122, 271-282 |
| M8 | The method assesses annual changes as well as seasonality (intra seasonal variations) |
| M9 | The impact model used has been widely applied and tested in various contexts |
| **Results** | |
| R1 | The results are explicit |
| R2 | The results are consistent and answer the question raised |
| R3 | The paper mentioned further information about the results. This can be for example limitations associated with the method that influence the results, uncertainties associated with the results, confidence intervals of the results, taking the results with caution etc. |
| R4 | The paper mentions what the results could be used for and by whom and / or some adaptation to palliate to the impacts identified by the results of the study |

| | |
|---|---|
| R5 | "The results are triangulated with one or several studies. None of the author from the assessment study is an author or co-author of a study used for triangulation of the results" |

## Appendix B- Data: Peer-reviewed articles included in the systematic review and their characteristics

**Table 3**: Peer-reviewed articles included in this study

| # | **Article full reference** |
|---|---|
| 1 | Aronica, G. T. and B. Bonaccorso (2013). "Climate change effects on hydropower potential in the Alcantara River basin in Sicily (Italy)." Earth Interactions 17(19). |
| 2 | Baltas, E. and M. Karaliolidou (2010). "Land use and climate change impacts on the reliability of hydroelectric energy production." Strategic Planning for Energy and the Environment 29(4): 56-63. |
| 3 | Barstad, I., A. Sorteberg and M. D. S. Mesquita (2012). "Present and future offshore wind power potential in northern Europe based on downscaled global climate runs with adjusted SST and sea ice cover." Renewable Energy 44: 398-405. |
| 4 | Bellarby, J., M. Wattenbach, G. Tuck, M. J. Glendining and P. Smith (2010). "The potential distribution of bioenergy crops in the UK under present and future climate." Biomass and Bioenergy 34(12): 1935-1945. |
| 5 | Bloom, A., V. Kotroni and K. Lagouvardos (2008). "Climate change impact of wind energy availability in the Eastern Mediterranean using the regional climate model PRECIS." Natural Hazards and Earth System Sciences 8(6): 1249-1257. |
| 6 | Burnett, D., E. Barbour and G. P. Harrison (2014). "The UK solar energy resource and the impact of climate change." Renewable Energy 71: 333-343. |
| 7 | Carless, D. and P. G. Whitehead (2013). "The potential impacts of climate change on hydropower generation in Mid Wales." Hydrology Research 44(3): 495-505. |
| 8 | Chernet, H. H., K. Alfredsen and Å. Killingtveit (2013). "The impacts of climate change on a Norwegian high-head hydropower system." Journal of Water and Climate Change 4(1): 17-37. |
| 9 | Cosentino, S. L., G. Testa, D. Scordia and E. Alexopoulou (2012). "Future yields assessment of bioenergy crops in relation to climate change and technological development in Europe." Italian Journal of Agronomy 7(2): 154-166. |
| 10 | Cradden, L. C., G. P. Harrison and J. P. Chick (2012). "Will climate change impact on wind power development in the UK?" Climatic Change 115(3-4): 837-852. |
| 11 | Crook, J. A., L. A. Jones, P. M. Forster and R. Crook (2011). "Climate change impacts on future photovoltaic and concentrated solar power energy output." Energy and Environmental Science 4(9): 3101-3109. |
| 12 | Dowling, P. (2013). "The impact of climate change on the European energy system." Energy Policy 60: 406-417. |
| 13 | Finger, D., G. Heinrich, A. Gobiet and A. Bauder (2012). "Projections of future water resources and their uncertainty in a glacierized catchment in the Swiss Alps and the subsequent effects on hydropower production during the 21st century." Water Resources Research 48(2). |
| 14 | Flörke, M., I. Bärlund and E. Kynast (2012). "Will climate change affect the electricity production sector? A European study." Journal of Water and Climate Change 3(1): 44-54. |
| 15 | Gaetani, M., T. Huld, E. Vignati, F. Monforti-Ferrario, A. Dosio and F. Raes (2014). "The near future availability of photovoltaic energy in Europe and Africa in climate-aerosol modeling experiments." Renewable and Sustainable Energy Reviews 38: 706-716. |
| 16 | Gaudard, L., F. Romerio, F. Dalla Valle, R. Gorret, S. Maran, G. Ravazzani, M. Stoffel and M. Volonterio (2014). "Climate change impacts on hydropower in the Swiss and Italian Alps." Science of the Total Environment 493: 1211-1221. |
| 17 | Golombek, R., S. A. C. Kittelsen and I. Haddeland (2012). "Climate change: Impacts on electricity markets in Western Europe." Climatic Change 113(2): 357-370. |
| 18 | Gunderson, I., S. Goyette, A. Gago-Silva, L. Quiquerez and A. Lehmann (2015). "Climate and land-use change impacts on potential solar photovoltaic power generation in the Black Sea region." Environmental Science and Policy 46: 70-81. |
| 19 | Hamududu, B. and A. Killingtveit (2012). "Assessing climate change impacts on global hydropower." Energies 5(2): 305-322. |
| 20 | Harrison, G. P., L. C. Cradden and J. P. Chick (2008). "Preliminary assessment of climate change impacts on the UK Onshore wind energy resource." Energy Sources, Part A: Recovery, Utilization and Environmental Effects 30(14-15): 1286-1299. |
| 21 | Harrison, G. P. and A. R. Wallace (2005). "Climate sensitivity of marine energy." Renewable Energy 30(12): 1801-1817. |
| 22 | Hoffmann, B., S. Häfele and U. Karl (2013). "Analysis of performance losses of thermal power plants in Germany - A System Dynamics model approach using data from regional climate modelling." Energy 49(1): 193-203. |
| 23 | Hueging, H., R. Haas, K. Born, D. Jacob and J. G. Pinto (2013). "Regional changes in wind energy potential over Europe using regional climate model ensemble projections." Journal of Applied Meteorology and Climatology 52(4): 903-917. |
| 24 | Koch, H., S. Vögele, F. Hattermann and S. Huang (2014). "Hydro-climatic conditions and thermoelectric electricity generation - Part II: Model application to 17 nuclear power plants in Germany." Energy 69: 700-707. |
| 25 | Koch, H., S. Vögele, F. F. Hattermann and S. Huang (2015). "The impact of climate change and variability on the generation of electrical power." Meteorologische Zeitschrift 24(2): 173-188. |
| 26 | Lehner, B., G. Czisch and S. Vassolo (2005). "The impact of global change on the hydropower potential of Europe: A model-based analysis." Energy Policy 33(7): 839-855. |

| # | **Article full reference** |
|---|---|
| 27 | Majone, B., F. Villa, R. Deidda and A. Bellin (2015). "Impact of climate change and water use policies on hydropower potential in the south-eastern Alpine region." Science of the Total Environment. |
| 28 | Maran, S., M. Volonterio and L. Gaudard (2014). "Climate change impacts on hydropower in an alpine catchment." Environmental Science and Policy 43: 15-25. |
| 29 | McColl, L., E. J. Palin, H. E. Thornton, D. M. H. Sexton, R. Betts and K. Mylne (2012). "Assessing the potential impact of climate change on the UK's electricity network." Climatic Change 115(3-4): 821-835. |
| 30 | Mimikou, M. A. and E. A. Baltas (1997). "Climate change impacts on the reliability of hydroelectric energy production." Hydrological Sciences Journal 42(5): 661-678. |
| 31 | Naughton, M., R. C. Darton and F. Fung (2012). "Could climate change limit water availability for coal-fired electricity generation with carbon capture and storage? A UK case study." Energy and Environment 23(2): 265-282. |
| 32 | Nolan, P., P. Lynch, R. McGrath, T. Semmler and S. Wang (2012). "Simulating climate change and its effects on the wind energy resource of Ireland." Wind Energy 15(4): 593-608. |
| 33 | Panagea, I. S., I. K. Tsanis, A. G. Koutroulis and M. G. Grillakis (2014). "Climate change impact on photovoltaic energy output: The case of Greece." Advances in Meteorology 2014. |
| 34 | Pašičko, R., Č. Branković and Z. Šimić (2012). "Assessment of climate change impacts on energy generation from renewable sources in Croatia." Renewable Energy 46: 224-231. |
| 35 | Pereira-Cardenal, S. J., H. Madsen, K. Arnbjerg-Nielsen, N. Riegels, R. Jensen, B. Mo, I. Wangensteen and P. Bauer-Gottwein (2014). "Assessing climate change impacts on the Iberian power system using a coupled water-power model." Climatic Change 126(3-4): 351-364. |
| 36 | Pryor, S. C., R. J. Barthelmie and E. Kjellström (2005). "Potential climate change impact on wind energy resources in northern Europe: Analyses using a regional climate model." Climate Dynamics 25(7-8): 815-835. |
| 37 | Pryor, S. C., J. T. Schoof and R. J. Barthelmie (2005). "Climate change impacts on wind speeds and wind energy density in Northern Europe: Empirical downscaling of multiple AOGCMs." Climate Research 29(3): 183-198. |
| 38 | Reeve, D. E., Y. Chen, S. Pan, V. Magar, D. J. Simmonds and A. Zacharioudaki (2011). "An investigation of the impacts of climate change on wave energy generation: The Wave Hub, Cornwall, UK." Renewable Energy 36(9): 2404-2413. |
| 39 | Reyers, M., J. G. Pinto and J. Moemken (2015). "Statistical-dynamical downscaling for wind energy potentials: Evaluation and applications to decadal hindcasts and climate change projections." International Journal of Climatology 35(2): 229-244. |
| 40 | Richert, C. N. and A. Matzarakis (2014). "The climatic wind energy potential — present and future: GIS-analysis in the region of Freiburg im Breisgau based on observed data and Regional Climate Models." Central European Journal of Geosciences 6(2): 243-255. |
| 41 | Santos, J. A., C. Rochinha, M. L. R. Liberato, M. Reyers and J. G. Pinto (2015). "Projected changes in wind energy potentials over Iberia." Renewable Energy 75: 68-80. |
| 42 | Schaefli, B., B. Hingray and A. Musy (2007). "Climate change and hydropower production in the Swiss Alps: Quantification of potential impacts and related modelling uncertainties." Hydrology and Earth System Sciences 11(3): 1191-1205. |
| 43 | Seljom, P., E. Rosenberg, A. Fidje, J. E. Haugen, M. Meir, J. Rekstad and T. Jarlset (2011). "Modelling the effects of climate change on the energy system-A case study of Norway." Energy Policy 39(11): 7310-7321. |
| 44 | Tobin, I., R. Vautard, I. Balog, F. M. Bréon, S. Jerez, P. M. Ruti, F. Thais, M. Vrac and P. Yiou (2014). "Assessing climate change impacts on European wind energy from ENSEMBLES high-resolution climate projections." Climatic Change 128(1-2): 99-112. |
| 45 | Torssonen, P., A. Kilpeläinen, H. Strandman, S. Kellomäki, K. Jylhä, A. Asikainen and H. Peltola (2015). "Effects of climate change and management on net climate impacts of production and utilization of energy biomass in Norway spruce with stable age-class distribution." GCB Bioenergy. |
| 46 | Tuck, G., M. J. Glendining, P. Smith, J. I. House and M. Wattenbach (2006). "The potential distribution of bioenergy crops in Europe under present and future climate." Biomass and Bioenergy 30(3): 183-197. |
| 47 | Van Vliet, M. T. H., S. Vögele and D. Rübbelke (2013). "Water constraints on European power supply under climate change: Impacts on electricity prices." Environmental Research Letters 8(3). |
| 48 | Van Vliet, M. T. H., J. R. Yearsley, F. Ludwig, S. Vögele, D. P. Lettenmaier and P. Kabat (2012). "Vulnerability of US and European electricity supply to climate change." Nature Climate Change 2(9): 676-681. |
| 49 | Wachsmuth, J., A. Blohm, S. Gößling-Reisemann, T. Eickemeier, M. Ruth, R. Gasper and S. Stührmann (2013). "How will renewable power generation be affected by climate change? The case of a metropolitan region in Northwest Germany." Energy 58: 192-201. |
| 50 | Westaway, R. (2000). "Modelling the potential effects of climate change on the Grande Dixence hydro-electricity scheme, Switzerland." Journal of the Chartered Institution of Water and Environmental Management 14(3): 179-185. |

**Table 4**: Detailed characteristics of the peer-reviewed articles and individual results included in this study

| # | Emission scenario(s) used | Climate model(s)/projection(s) used | Period of assessment (Near term to mid-21st century) | Period of assessment (End of the 21st century) | Baseline / Control | Energy type | Impact model used | Geo-graphical coverage | Number of individual result considered in the analysis | Source of funding |
|---|---|---|---|---|---|---|---|---|---|---|
| **1** | IPCC SRES A2 and B2 | Monte Carlo simulations (first-order Markov chain and an autoregressive moving average (ARMA) model) | 2013–2037 | | 1971–2000 | Hydro | Rainfall–runoff model: IHACRES | Alcantara River Basin, Sicily (Italy) | 2 | European Commission (FP5 project) |
| **2** | Response to a doubling of effective CO2 concentration | Hadley Centre Coupled Model HadCM2 | 2008-2050 | | 1971-2002 | Hydro | Reservoir operation model developed in the study. It simulates a water budget model | Ilarion reservoir, Greece | 1 | Not mentioned |
| **3** | IPCC SRES A1B | Ensemble of four CGCMs: GFDL V2.0 (T42); ECHAM5 (T42); HADCM3 (T42); CCSM3 (T85) | 2020-2049 | | | Wind | Downscaling of data from four CGCMs to estimate the future wind power production potential at the 100 m level | Northern Europe | 4 | Norwegian Research Council |
| **4** | UKCP02 model for scenarios at Low, Medium-Low, Medium-High and High emissions | The UKCIP02 data have been developed on the basis of HadCM3, which drove the regional model (HadRM3) (Modelling not performed in the study; i.e. the study uses the UKCP02 projections) | | 2080s | | Bioenergy | Map of the geographical suitability cover for the crops. The baseline suitability cover was compared to the actual agricultural land use in the year 2005 | UK | Not included in analysis | UK DEFRA |
| **5** | IPCC SRES A2 | Hadley Centre's PRECIS Regional Climate Modelling System | | 2071-2100 | 1961-1990 | Wind | The PRECIS regional model over the East Mediterranean is used to dynamically downscaled the results of the Had3CM GCM. Wind field changes are determined by comparing the current climate simulation with the IPCC A2 emissions scenario simulation. The consistency of the current climate simulation of wind speeds is assessed by comparing its results to the ERA40 re-analysis data. | Eastern Mediter-ranean (EM) | 4 | Not mentioned |

| # | Emission scenario(s) used | Climate model(s)/projection(s) used | Period of assessment (Near term to mid-21st century) | Period of assessment (End of the 21st century) | Baseline / Control | Energy type | Impact model used | Geo-graphical coverage | Number of individual result considered in the analysis | Source of funding |
|---|---|---|---|---|---|---|---|---|---|---|
| **6** | UKCP09 low, medium high scenarios | The UKCP09 data have been developed using the Hadley Centre Coupled Model, version 3 (HadCM3) (the study only uses the projection data and does not perform the modelling) | 2040-2069 (2050s) | 2070-2099 (2080s) | 1961-1990 | Solar | The projected average percentage change of horizontal surface solar irradiance can be calculated for the 2050s and 2080s by projecting the UKCP09 climate change values onto the baseline solar irradiance model | UK | 42 | UK Engineering and Physical Sciences Research Council and UK Energy Research Centre studentship |
| **7** | UKCP09 medium and high emission scenarios | UKCP09 data | 2010-2029 (2020s) and 2040-2059 (2050s) | | 1961-1990 | Hydro | Rainfall–runoff model: IHACRES | Wales, UK | 3 | Not mentioned |
| **8** | IPCC SRES A2 and B2 (HadAm3H) and IPCC SRES B2 (ECHAM4) | Two AOGCM: the Max Planck Institute general circulation model ECHAM4 and the Hadley Centre general circulation model HadAM3H developed from the component of the AOGCM HadCM3 | | 2071–2100 | 1961–1990 | Hydro | HBV (Hydrologiska Byråns Vattenbalansavdelning) hydrological model and the nMAG hydropower simulation model | Small scale hydropower plant in Norway (the Aurland hydropower system) | 3 | Norwegian Research Council |
| **9** | None directly: Used results from studies that took the IPCC SRES A2 or using double CO2 level | None directly (the study uses future crop yields from existing studies using the IPCC SRES A2 scenario or using double CO2 level) | 2020 and 2030 | | Average value 2003-2007 | Bioenergy | Future yields were assessed according to two factors: technological development and climate change. the former was based on prospect of DG-Agriculture for conventional crops and expert judgments for bioenergy crops, while the latter based on relevant research papers and literature reviews which used site-specific crop growth models | European Union | Not included in analysis | European Commission (FP7) |

| # | Emission scenario(s) used | Climate model(s)/projection(s) used | Period of assessment (Near term to mid-21st century) | Period of assessment (End of the 21st century) | Baseline / Control | Energy type | Impact model used | Geo-graphical coverage | Number of individual result considered in the analysis | Source of funding |
|---|---|---|---|---|---|---|---|---|---|---|
| **10** | IPCC SRES A2 (HadCM3) and IPCC SRES A2, A1B, B1 (ECHAM5) | ECHAM5 from the Max Planck Institute for Meteorology and the Hadley Centre's HadCM3 | | 2081-2100 | 1961-1990 | Wind | The authors derive GCM geostrophic wind and use it as a proxy indicator | UK | 4 | UK Engineering and Physical Sciences Research Council (EPSRC) |
| **11** | IPCC SRES A1B | HadGEM1 and HadCM3 from the World Climate Research Programme's (WCRP's) Coupled Model Intercomparison Project phase 3 (CMIP3) multi-model dataset | 2010 to 2080 | 2010 to 2080 | 1980–1999 | Solar | General equations are used for PV and CSP technologies to calculate the power output as a function of irradiance and ambient temperature | California, Nevada, Spain, Algeria (north), Germany (south), Saudi Arabia, China (south), Australia (south) | 16 | Not mentioned |

| # | Emission scenario(s) used | Climate model(s)/projection(s) used | Period of assessment (Near term to mid-21st century) | Period of assessment (End of the 21st century) | Baseline / Control | Energy type | Impact model used | Geo-graphical coverage | Number of individual result considered in the analysis | Source of funding |
|---|---|---|---|---|---|---|---|---|---|---|
| **12** | NoC—No climate run has been applied to the energy system, as in traditional energy system modelling. This is the reference case to which the KNMI, METO, DMI and MPI climate runs are compared. KNMI: A representative average or central climate run based on an A1B baseline energy system scenario. METO: Show significant deviations from the average climate run, usually warmer and drier than the average, based on an A1B baseline energy system scenario. DMI: Show significant deviations from the average climate run, usually colder and wetter than the average, based on an A1B baseline energy system scenario. MPI: A representative average or central climate run based on an E1B emissions reduction energy system scenario | Data taken from the ENSEMBLE project. The ENSEMBLES project developed probabilistic estimates of uncertainty in future climate based on state-of-the-art, high resolution, global and regional Earth System models. | 2050 | | There is a no-climate-change-impact run for both the A1B and the E1 scenarios (called no C-A1B and no C-E1, respectively) | Thermal, hydro, wind, solar | A modified POLES model was used (Prospective Outlook for the Long-term Energy System) | EU27 | 0 | Not mentioned |
| **13** | IPCC SRES A1B | Used data from 7 RCMs ensemble available from the EU FP6 Integrated Project ENSEMBLES: | 2037 to 2064 | 2071-2098 | 1992 to 2019 | Hydro | A rainfall-runoff model: the modified topographic kinematic approximation and integration model (TOPKAPI) | Vispa valley, Switzerland (Mattmarkse ereservoir) | 2 | European Commission (FP6 and FP7) |
| **14** | IPCC A2 scenario | IPSL-CM4 model from the Institute Pierre Simon Laplace, France (IPCM.4) and MIROC3.2 model From the Center for Climate System Research, University of Tokyo, Japan (MIMR) | 2040-2069 (2050s) | | 1961-1990 | Thermal | The Water Use model of WaterGAP3 covering the covering the whole of Europe | Europe | 2 | European Commission (FP6) |

| # | Emission scenario(s) used | Climate model(s)/projection(s) used | Period of assessment (Near term to mid-21st century) | Period of assessment (End of the 21st century) | Baseline / Control | Energy type | Impact model used | Geo-graphical coverage | Number of individual result considered in the analysis | Source of funding |
|---|---|---|---|---|---|---|---|---|---|---|
| **15** | IPCC SRES B2 and three different combinations of aerosols emissions scenarios: (1) in the 2030GHG experiment, aerosols emissions are kept at the 2000 level; (2) in the 2030 CLEMFR experiment, MFR (Maximum Feasible Reduction) is assumed in continental Europe and CLE (Current LEgislation) elsewhere; (3) in the 2030MFR experiment, MFR is assumed worldwide. | ECHAM5-HAM aerosol-climate model | year 2030 | | year 2000 | Solar | The photovoltaic performance model used in this study integrates climate variables in a model for inclined-plane irradiation and photovoltaic system output. | Europe | 2 | European Commission Joint Research Centre |

| # | Emission scenario(s) used | Climate model(s)/projection(s) used | Period of assessment (Near term to mid-21st century) | Period of assessment (End of the 21st century) | Baseline / Control | Energy type | Impact model used | Geo-graphical coverage | Number of individual result considered in the analysis | Source of funding |
|---|---|---|---|---|---|---|---|---|---|---|
| **16** | A merging of dynamic and stochastic downscaling (Upper Rgne and Val d'Aosta case studies)<br>A point scale meteorological forcing computed from RCM simulations with a quantile based error correction approach (Toce case studies)<br>The resulting daily scenarios were further refined to 3-hourly time series, using sub-daily data from the RCMs | Two regional climate models (RCMs), the REMO and the RegCM3 | 2031–2050 | | Past periods are 1991–2010 for Switzerland and 2001–2010 for Italy. | Hydro | Combination of hydrologic and economic models<br>*Hydrological models*<br>Future hydrological data was obtained with different models. For the Upper Rhone and the Val d'Aosta case studies, data was generated with the TOPKAPI. For the Toce case study, data was obtained with the FEST-WB distributed water balance model.<br>*Electricity prices models*<br>Switzerland (Upper Rhone Valley): GARCH model of spot prices &<br>Italy: Energy Value Index (EVI)<br>*Management models*<br>Hydrological and electricity prices models outputs feed the management models: Swiss case study: a binary local search algorithm, so-called Threshold Accepting & for Val d'Aosta: SOLARIS & for Toce: BPMPD Solver | Three neighbouring catchments in the Alps were selected in Switzerland and Italy, i.e. Valais (Mattmark Dam), Val d'Aosta (17 inter-connected hydropower plants and in depth studies for Valpelline and Hone II) and Toce (18 plants: 6 run of river plants and 12 storage plants) | 10 | European Commission (FP7); Research Fund for the Italian Electrical System under the Contract Agreement between RSE and the Ministry of Economic Development<br>General Directorate for Nuclear Energy, Renewable Energy and Energy Efficiency |

| # | Emission scenario(s) used | Climate model(s)/projection(s) used | Period of assessment (Near term to mid-21st century) | Period of assessment (End of the 21st century) | Baseline / Control | Energy type | Impact model used | Geo-graphical coverage | Number of individual result considered in the analysis | Source of funding |
|---|---|---|---|---|---|---|---|---|---|---|
| **17** | IPCC SRES A1B | Hadley Center Coupled Model (HadCM3) and the Max Planck Institute model ECHAM5 | | 2070-2099 (2080s) | 1961–1990 | Hydro, Thermal | Multi-market equilibrium model LIBEMOD | Western European (Austria, Belgium/Luxemburg, Denmark, Finland, France, Germany, Greece, Ireland/Eire, Italy, Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, United Kingdom.) | 37 | Research Council of Norway |

| # | Emission scenario(s) used | Climate model(s)/projection(s) used | Period of assessment (Near term to mid-21st century) | Period of assessment (End of the 21st century) | Baseline / Control | Energy type | Impact model used | Geo-graphical coverage | Number of individual result considered in the analysis | Source of funding |
|---|---|---|---|---|---|---|---|---|---|---|
| **18** | IPCC SRES A2 and B2 | HIRHAM model driven by the United Kingdom's Hadley Center HadAM3H GCM. | | 2071-2100 | 1961-1990 | Solar | Simulated data are used to determine potential change in climate and land-use according to two different development scenarios. Incident solar radiation flux from re-analyses, spatial interpolation, and the application of the Delta change method are used to assess the current and future solar resource potential within this catchment. Potential sites suitable for PV power plants are selected following a Fuzzy logic approach, and thus the total potential solar energy through PV power generation can be determined. | Black Sea catchment | 1 | European Commission (FP7) |
| **19** | IPCC A1B | 12 GCMs<br>CGHR CGCM3.1 (T63), ECHOG, FGOALS FGOALS-g1.0, LASG, GFCM20 GFDL-CM2.0, GFCM21 GFDL-CM2.1, GIEH GISS-EH, NASA, HADCM3 UKMO-HadCM3, HADGEM UKMO-HadGEM1, MIHR MIROC3.2, MPEH5 MPEH5:, MRCGCM MRI-CGCM2.3.2, NCCCSM CCSM3 | Computed future for 2050 | | Baseline for 2005 | Hydro | Relating the runoff changes to hydropower generation potential through geographical information system (GIS), based on 2005 hydropower generation.<br>Then changes in water resource availability were converted in to changes in hydropower generation. | Global (all world) | 4 | Norwegian Research Council |

| # | Emission scenario(s) used | Climate model(s)/projection(s) used | Period of assessment (Near term to mid-21st century) | Period of assessment (End of the 21st century) | Baseline / Control | Energy type | Impact model used | Geo-graphical coverage | Number of individual result considered in the analysis | Source of funding |
|---|---|---|---|---|---|---|---|---|---|---|
| **20** | UKCIP02 low, medium high scenarios | UKCP02 data | | 2071-2100 (2080s) | 1961–1990 | Wind | The mean monthly value was used to generate a Rayleigh distribution that was then combined with the turbine production characteristics to estimate production.<br>The turbine chosen for this study was the 3 MW Vestas V90. The V90 possesses a 90 m diameter rotor at 80 m hub height.<br>With the UKCIP wind data available only at 10 m height, a correction was applied to translate it into higher speeds experienced at the 80 m hub height of the wind turbine. | UK but also assessment at five locations around the UK were selected to cover a range of different regions: two in England and one each in Scotland, Wales, and Northern Ireland | 14 | UK Engineering and Physical Sciences Research Council and Scottish Funding Council for the Joint Research Institute with Heriot-Watt University |
| **21** | Simulations by altering the mean annual wind speed by up to +/- 20% in 10% intervals | Changes in marine climate were simulated by altering the mean annual wind speed by up to+/- 20% in 10% intervals. (did not use GCM but probability distribution) | No specific period | | | Wave | Use of a Wave Energy Converter (WEC) developed by Edinburgh-based Ocean Power Delivery Ltd. The Pelamis is a 120 m long floating device that resembles a sea-snake with four articulated sections that flex (and produce up to 750 kW) as waves run down the length of the device. | Scottish West Coast (UK) | Not included in analysis | Not mentioned |

| # | Emission scenario(s) used | Climate model(s)/projection(s) used | Period of assessment (Near term to mid-21st century) | Period of assessment (End of the 21st century) | Baseline / Control | Energy type | Impact model used | Geo-graphical coverage | Number of individual result considered in the analysis | Source of funding |
|---|---|---|---|---|---|---|---|---|---|---|
| **22** | IPCC SRES A1B, A2, and B1 | regional climate model REMO (UBA run) | 2011-2040; 2041-2070 | | 1961-1990 | Thermal | Modelling thermal power plant units and their respective cooling systems through dynamic simulation taking into account legal thresholds for heat discharges to river water together with climate data projections (SRES scenarios A1B, A2, and B1). | Germany (26 German power plants are analyzed, both coal and nuclear and only units that were operating at the end of 2010 are considered.) | 12 | Not mentioned |
| **23** | IPCC SRES A1B | Two different RCMs are considered in this study:1) COSMO CLM and 2)REMO driven by ECHAM5/MPI-OM1 simulations | | 2061-2100 | 1961–2000 | Wind | The quantity Eout is computed from the wind velocities in 80 m. Wind turbine characteristics are assumed as following a 2.5-MW wind turbine from the GeneralElectricCo., Inc. | Europe | 11 | German Federal Ministry of Education and Research (BMBF) |

| # | Emission scenario(s) used | Climate model(s)/projection(s) used | Period of assessment (Near term to mid-21st century) | Period of assessment (End of the 21st century) | Baseline / Control | Energy type | Impact model used | Geo-graphical coverage | Number of individual result considered in the analysis | Source of funding |
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| **24** | Created using the statistical regional climate model STAR | STARS (STatistical Analogue Resampling Scheme (STARS) is based on the assumption that already observed weather situations will very likely recur in the same or similar way in the near future.) | 2008-2052 | | 1951-2009 | Thermal | An approach is applied here for analysing links between water availability and water temperature, air temperature and electricity generation by power plants. A highly disaggregated level is used combining a power plant model and hydrological models. It is applied to analyse effects of climate change on 17 nuclear power plants in Germany.<br>Because cooling systems, hydro-climatic conditions and the related legal restrictions differ for the different power plants, a separate consideration of each power plant is necessary. | Germany (17 nuclear power plants in Germany) | 1 | German Federal Environment Agency (Umweltbundesamt) |

| # | Emission scenario(s) used | Climate model(s)/projection(s) used | Period of assessment (Near term to mid-21st century) | Period of assessment (End of the 21st century) | Baseline / Control | Energy type | Impact model used | Geo-graphical coverage | Number of individual result considered in the analysis | Source of funding |
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| 25 | RCP2.6, RCP 8.6 | Applying the statistical regional climate model STARS (STatistical Analog Resampling Scheme) Gerstengarbe et al. (2015) produce 100 realizations (ensemble runs) for each scenario | 2031-2060 | | 1981–2010 | Hydro, Thermal, Wind | Thermal:<br>River discharge is simulated using the ecohydrological model SWIM. Thermal conditions in the surface waters next to the power plants were simulated using a water temperature model developed for the river Elbe by Koch and Grünewald (2010). Water temperature models were then developed.<br>Hydro:<br>River discharge is simulated using the ecohydrological model SWIM<br>Wind:<br>Long-term wind speed at 80m over ground as calculated by the DWD (2008). | Germany | 7 | Not mentioned |
| 26 | Set of scenario assumptions for changes in human water use, which are largely are largely consistent with the no-climate-policy IPCC-IS92a and the intermediate Baseline-A scenario as developed by the Dutch National Institute of Public Health and Environment (RIVM). This global emission pathway is also within the range of marker scenarios of the updated IPCC-SRES scenarios, and slightly above their intermediate 'A1B' scenario | HadCM3 model and the ECHAM4/OPYC3 model | 2050s | 2080s | 1961–1990 | Hydro | Integrated global water model WaterGAP (Water—Global Assessment and Prognosis). WaterGAP comprises two main components, a Global Hydrology Model and a Global Water Use Model. | Europe Within this study, the geographic extent of Europe is defined to include the European part of Russia (limited by the Ural Mountains) to the east and Turkey to the south. | 146 | German Federal Ministry of Education, Science, Research and Technology (BMBF) |

| # | Emission scenario(s) used | Climate model(s)/projection(s) used | Period of assessment (Near term to mid-21st century) | Period of assessment (End of the 21st century) | Baseline / Control | Energy type | Impact model used | Geo-graphical coverage | Number of individual result considered in the analysis | Source of funding |
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| **27** | IPCC SRES A1B | The 4 selected climate models are listed in the following with their acronyms, which refer to the corresponding driving GCM first three characters) and nested RCM (last three characters), respectively: i) ‘HCH–RCA’ = HadCM3–High Sensitivity (UK) driving RCA (Sweden); ii) ‘ECH-RMO’ = ECHAM5/MPI (Germany) driving RACMO2 (Netherlands); iii) ‘ECH–REM’ = ECHAM5/MPI (Germany) driving REMO (Germany); and vi) ‘ECH–RCA’=ECHAM5/MPI (Germany) driving RCA (Sweden) | 2040–2070 | | 1970–2000 | Hydro | The semi-distributed modeling system GEOTRANSF. | Italy Noce catchment, which is located in the Southeastern Alps, Italy (5 hydropower plants considered in the present study) | 5 | European Commission and Italian Ministry of Public Instruction, University and Research |

| # | Emission scenario(s) used | Climate model(s)/projection(s) used | Period of assessment (Near term to mid-21st century) | Period of assessment (End of the 21st century) | Baseline / Control | Energy type | Impact model used | Geo-graphical coverage | Number of individual result considered in the analysis | Source of funding |
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| **28** | IPCC SRES A1B | ECHAM General Circulation Model. These global projections were downscaled through two different Regional Climate Models, REMO and RegCM | ‘‘Middle’’ refers to the near future (from 2011 to 2030) and ‘‘Future’’ refers to the far future (from 2031 to 2050). | | 2002 and 2010 | Hydro | The hydrological simulations were provided by ETHZ using TOPKAPI model (Ciarapica and Todini, 2002), a rainfall–runoff model that handles the topography and a representation of below ground in three layers.<br><br>The management of hydropower systems was simulated with a simple optimization tool, called SOLARIS (Maran et al., 2006) developed by RSE, that allows the user to identify the optimal management of a network of hydroelectric reservoirs. | Italy hydropower system in Valle d’Aosta Region in Italy. | 4 | European Commission and Research Fund for the Italian Electrical System under the Contract Agreement between RSE (formerly known as ERSE) and the Ministry of Economic Development – General Directorate for Nuclear Energy, Renewable Energy and Energy Efficiency |
| **29** | IPCC SRES A1B | Eleven HadRM3 model variants (Met Office Hadley Centre) | 2020-2080 | 2020-2080 | 1st March 1990 to 31st April 2009 | Electricity network | By formalising the current relationship between weather-related faults and weather, the authors use climate projections from a regional climate model (RCM) to quantitatively assess how the frequency of these faults may change in the future. | UK | Not included in analysis | UK Energy Networks Association |

| # | Emission scenario(s) used | Climate model(s)/projection(s) used | Period of assessment (Near term to mid-21st century) | Period of assessment (End of the 21st century) | Baseline / Control | Energy type | Impact model used | Geo-graphical coverage | Number of individual result considered in the analysis | Source of funding |
|---|---|---|---|---|---|---|---|---|---|---|
| 30 | Two equilibrium scenarios (UK Meteorological Office High Resolution model, UKHI and Canadian Climate Centre model, CCC) referring to years 2020, 2050 and 2100 and one transient scenario (UK High Resolution Transient output, UKTR) referring to years 2032 and 2080 were applied to represent both "green- house" warming and induced changes in precipitation and potential evapotranspiration. The two equilibrium experiments using high resolution atmospheric GCM (UKHI and CCC) and assuming the standard 1992 IPCC emissions scenario, a "central" climate sensitivity of 2.5°C and ignoring the effects of sulphate aerosols, produced climate change scenarios for the years, 2020, 2050 and 2100. The transient experiment UKTR, using the high resolution coupled ocean-atmosphere GCM of the Hadley Centre, gave climate change scenarios with a climate sensitivity of 2.5°C and assuming no sulphate aerosol effect corresponding to the years 2032 and 2080 respectively | The climate modelling followed the methodology developed by the Climatic Research Unit (CRU) of the University of East Anglia, UK. The methodology adopted used the CRU 1961-1990 baseline, climatologies for Europe, the results from three GCM (General Circulation Models) climate change experiments (UKHI, CCC and UKTR) and a range of projections of global warming calculated by MAGICC (Model for the Assessment of Greenhouse gas Induced Climate Change), a simple upwelling-diffusion energy balance climate model | 1 and 2: 1990-2100; 3-1990-2080 | 1 and 2: 1990-2100; 3-1990-2080 | 1961-1990 | Hydro | The operation of the Polyfyto reservoir is described by a model, which consists of the water budget under various constraints concerning storage volume, outflow from the reservoir and energy production. The reservoir water budget equation is applied on a monthly basis. | Greece (Polyfyto reservoir in northern Greece) | 2 | Commission of the European Communities, DG XII, Environment Programme |

| # | Emission scenario(s) used | Climate model(s)/projection(s) used | Period of assessment (Near term to mid-21st century) | Period of assessment (End of the 21st century) | Baseline / Control | Energy type | Impact model used | Geo-graphical coverage | Number of individual result considered in the analysis | Source of funding |
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| **31** | IPCC SRES A2 emission scenario were used to derive three climate change scenarios: dry, mean and wet, which correspond roughly to the 5th, 50th and 95th percentiles of flow projections | Six Global Climate models | 2011-2040 | | 1961-1990 | Thermal | The assessment investigates whether the number of days during which Hands-Off Flow conditions are reached and the power station in the catchment is forced to cease or reduce abstraction for electricity generation. | UK (Ferrybridge power station in Yorkshire) | 1 | Not mentioned |
| **32** | IPCC SRES A1B, A2, B1, B2 | Max Plank Institute's GCM, European Center Hamburg Model, is used to drive the Rossby Center's RCM (RCA3). | 2021-2060 | | 1961-2000 | Wind | RCA3 Model (No impact model per se) | Ireland | 2 | Environmental Protection Agency and the Higher Education Authority |
| **33** | IPCC SRES A1B | Five regional climate models of the ENSEMBLES (http://ensemblesrt3.dmi.dk/) database:<br>1- C4IRCA3 from SMHI, Sweden (Driven by HadCM3Q16)<br>2- ETHZ-CLM from ETHZ, Switzerland (driven by HadCM3Q0)<br>3- MPI-M-REMO, from MPI, Germany (driven by) ECHAM5-r3<br>4- SMHIRCA, from SMHI, Sweden (driven by BCM)<br>5- CNRM-RM5.1, from CNRM, France (driven by APREGE RM5.1) | 2011–2050 | 2061−2100 | 1950–2000 (for temperature) and 1985–2005 (for irradiance) | Solar | The potential percentage change in PV output is calculated through the fractional change $\Delta P$PV/$P$PV (from J. A. Crook, L. A. Jones, P. M. Forster, and R. Crook, "Climate change impacts on future photovoltaic and concentrated solar power energy output," Energy and Environmental Science, vol. 4, no. 9, pp. 3101–3109, 2011.) | Greece | 8 | European Commission (FP7) |

| # | Emission scenario(s) used | Climate model(s)/projection(s) used | Period of assessment (Near term to mid-21st century) | Period of assessment (End of the 21st century) | Baseline / Control | Energy type | Impact model used | Geo-graphical coverage | Number of individual result considered in the analysis | Source of funding |
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| **34** | IPCC SRES A2 | The climate data used for this assessment were taken from the global climate model ECHAM5-MPIOM and dynamically downscaled by the regional climate model RegCM at Croatian Meteorological and Hydrological Service (DHMZ) | 2011-2040; 2041-2070 | | 1961-1990 | Solar Wind Hydro | Solar: Climate modelling studies for Croatia made at DHMZ Wind: Electricity production from wind power plants is in the cubic relationship with wind speed, and it is proportional with air density Hydro.: The current practice in Croatia is that the Croatian Power Utility (HEP) forecasts the annual electricity production based on DHMZ data of aggregated water inflows into reservoirs. A linear relationship is assumed between the water inflow and the electricity production from hydro power plants. | Croatia | 3 | European Commission (FP7) |
| **35** | IPCC SRES A1B | Three different regional climate models (RCM) from the ENSEMBLES Project: These are: RACMO2, CLM, and REMO | 2036-2065 | | 1961-1990 | Hydro | A stochastic dynamic programming approach (see below) was used to formulate operating rules for hydropower generation in the Iberian system | Iberian Peinsula | 1 | Not mentioned |

| # | Emission scenario(s) used | Climate model(s)/projection(s) used | Period of assessment (Near term to mid-21st century) | Period of assessment (End of the 21st century) | Baseline / Control | Energy type | Impact model used | Geo-graphical coverage | Number of individual result considered in the analysis | Source of funding |
|---|---|---|---|---|---|---|---|---|---|---|
| **36** | IPCC SRES A2, B2 | Rossby Centre coupled Regional Climate Model (RCM) (RCAO) with boundary conditions derived from ECHAM4/ OPYC3 AOGCM and the HadAM3H atmosphere- only GCM | | 2071-2100 | 1961–1990 | Wind | To further explore the impact of potential changes in the speed distribution on the wind energy sector the authors computed the frequency of wind speeds in four classes that pertain to the operation of wind turbines in the 2–4 MW class (e.g. turbines such as the Vestas V-90 or GE 3.6s) | northern Europe | 3 | Nordic Energy Research (Nordisk Energiforskning) and the energy sector in the Nordic countries as well as the participating institutions |
| **37** | IPCC SRES A2 | 5 GCMS:<br>1- GFDL CM2.0 (GFDL) From Geophysical Fluid Dynamics Laboratory (NOAA, USA)<br>2- GISS ModelE-R (GISS) From Goddard Institute for Space Sceince USA<br>3- IPSL CM4 V1 (IPSL) From Institut Pierre Simon Laplace, France<br>4- MIROC3.2 medium resolution (MIROC) From Center for Climate System Research, University of Tokyo Frontier Research Center for Global Change<br>5- MRI_CGCM2.3.2a (MRI) From Meteorological Rsearch Institute of Japan | 2046-2065 | 2081-2100 | 1961-1990 | Wind | None: Empirical downscaling tools are used to output from 5 state-of-the-art AOGCMs to investigate projected changes in wind speeds and energy density in northern Europe. | northern Europe, and specifically the Baltic region | 1 | Nordic Energy Research; grants to Indiana University from IBM (Shared University Research) and the National Science Foundation |

| # | Emission scenario(s) used | Climate model(s)/projection(s) used | Period of assessment (Near term to mid-21st century) | Period of assessment (End of the 21st century) | Baseline / Control | Energy type | Impact model used | Geo-graphical coverage | Number of individual result considered in the analysis | Source of funding |
|---|---|---|---|---|---|---|---|---|---|---|
| **38** | IPCC SRES scenarios A1B and B1 | This study uses the Global Climate Model (GCM) and Regional Climate Model (RCM) wind output provided by the Max Planck Institute for Meteorology | | 2061-2100 | 1961-2000 | Wave | Use of a wave energy converter (WEC): The Wave Hub | Wave Hub, Cornwall, UK | Not included in analysis | |
| **39** | IPCC SRES A1B, B1, A2 | Statistical–dynamical downscaling (SDD) with the regional climate model COSMO-CLM | | 2061-2100 | | Wind | Use of wind turbine characteristics of an idealized 2.5MW wind turbine from General Electric (2010): | Special focus on Germany but results for other countries in Europe too | 11 | German Federal Ministry of Education and Research |
| **40** | IPCC SRES A1B, SRES B1 | regional climate models REMO and CLM | 2021-2050 | 2071-2100 | 1961-1990 | Wind | Use of a specific the 2.3 kW wind turbine ENERCON E-82 | South West Germany (Freiburg im Breisgau) | 2 | Not mentioned |
| **41** | IPCC SRES A1B | COSMO-CLM simulations driven by ECHAM5 | 2041-2070 | | | Wind | Use of the characteristics of a 2 MW E-82 E2 turbine from ENERCON GmbH | Iberia (northern Galicia (1); Burgos (2); Ebro valley (3); northern Portugal (4); Southern Cataluna (5); Oeste (6); Albacete (7); Southern Andalucía (8)) | 13 | Portuguese Foundation for Science and Technology and FEDER (Fundo Europeu de Desenvolvimento Regional) |

| # | Emission scenario(s) used | Climate model(s)/projection(s) used | Period of assessment (Near term to mid-21st century) | Period of assessment (End of the 21st century) | Baseline / Control | Energy type | Impact model used | Geo-graphical coverage | Number of individual result considered in the analysis | Source of funding |
|---|---|---|---|---|---|---|---|---|---|---|
| **42** | Results of the global mean warming - regional climate - scaling scaling methodology | The future local scale meteorological time series - namely daily mean precipitation and temperature - are generated by perturbing the observed series for a control period according to the method of Shabalova et al (2003). In this method, the perturbation of local scale precipitation and temperature is based on the corresponding regional scale outputs of a Regional Climate Model (RCM) for the same control and future period. | | 2070-2099 | 1961-1990 | Hydro | The simulation tool includes 4 types of models:<br>- a water management model<br>- a hydrological model<br>- a glacier surface evolution model<br>- a model for the generation of local scale meteorological time-series under a given climate change scenario<br><br>Climate change impacts on the management system are evaluated in terms of relative changes. Two types of indicators are used:<br>- some quantitative: one set evaluates the total annual electricity production and the other its seasonal distribution<br>- some qualitative, e.g. the Reliability-Resilience-Vulnerability (RRV) criteria | A Hydropower plant in the southern Swiss Alps (The dam of Mauvoisin) | 1 | EU Energy, Environment and Sustainable Development Programme and Swiss Federal Office for Education and Science |

| # | Emission scenario(s) used | Climate model(s)/projection(s) used | Period of assessment (Near term to mid-21st century) | Period of assessment (End of the 21st century) | Baseline / Control | Energy type | Impact model used | Geo-graphical coverage | Number of individual result considered in the analysis | Source of funding |
|---|---|---|---|---|---|---|---|---|---|---|
| **43** | IS92a (ECHAM4), IPCC SRES B2 (ECHAM4 and HadAM3H), IPCC SRES A2(HadAM3H), IPCC SRES A1B (BCM v2), CIMP2 (BCM v1), 1.63*CO2 (CAMSOslo) | Five different global models: the global climate model (GCM) data were provided from the Max Planck Institute, Germany (MPI), the Hadley Centre, U.K. (HC), the Bjerknes Centre, Norway (BCCR), and University of Oslo, Norway (UiO). The global models are geographically downscaled using the HIRHAM atmospheric regional climate model (RCM).<br>Ten climate experiments, based on five different global models and six emission scenarios, and are selected to cover the range of possible future climate scenarios. | 2031–2060 | | The first nine climate experimt: 70 years (1961–1990) The tenth experimt: 50 years (1981–2010) | Hydro, Wind | MARKAL<br>(MARKet ALocation) Norway model. MARKAL is a modelling tool developed by the Energy Technology System Analysis Programme (ETSAP), an implementing agreement of the International Energy Agency (IEA). | Norway | 1 | Research Council of Norway and the Norwegian Water Resources and Energy Directorate |
| **44** | IPCC SRES A1B (which lies between the IPCC AR5 RCP4.5 and RCP8.5 scenarios) | Ensemble of 15 regional climate projections achieved from 10 Regional Climate Models downscaling six Global Climate Models | 2031-2060 | 2071-2100 | 1951–2000 | Wind | Wind speed at the turbine height is converted into EWP using a standard modern turbine power curve. The power curve shape is derived from interpolated manufacturer data (for the VESTAS V90-3 MW) normalized by the turbine nominal (i.e. maximum) power.<br>The power curve is then scaled by the nominal power of the turbines under consideration in the analysis. | Europe | 20 | European Commission (FP7 and FP6) |

| # | Emission scenario(s) used | Climate model(s)/projection(s) used | Period of assessment (Near term to mid-21st century) | Period of assessment (End of the 21st century) | Baseline / Control | Energy type | Impact model used | Geo-graphical coverage | Number of individual result considered in the analysis | Source of funding |
|---|---|---|---|---|---|---|---|---|---|---|
| **45** | IPCC SRES B1 and A2 scenarios | ? | 80 years fixed rotation length | | 1971–2000 | Bioenergy | Use of a forest ecosystem model | Norway spruce forest area in central Finland | Not included in analysis | Graduate School in Forest Sciences (GSForest), University of Eastern Finland (UEF) and the School of Forest Sciences |
| **46** | IPCC SRES emission scenarios, A1FI, A2, B1 and B2 | Four global climate models, HadCM3, CSIRO2, PCM and CGCM2 | 2020 and 2050 | 2080s | 1961–1990 | Bioenergy | Use of simple rules for suitable climatic conditions and elevation. | Europe | Not included in analysis | |
| **47** | IPCC SRES A2 (medium–high) and B1 (low) emission scenarios | Biased-corrected general circulation model (GCM) output (Hagemann et al 2011). In the study by Hageman et al, they use 3 GCMs but difficult to say whether the author of this publication also used 3 GCMs as not explicit | 2031–2060 | | 1971–2000 | Hydro, Thermal | Thermal: Thermal electric power production model (Koch and Vogele 2009, Rubbelke and Vogele 2011)<br>Hydro: gross hydropower potential is directly calculated from gridded datasets of water availability and elevation differences, without requiring additional data of exact location and installed capacities of hydropower plants Lehner et al (2005). | Europe | 81 | European Commission |

| # | Emission scenario(s) used | Climate model(s)/projection(s) used | Period of assessment (Near term to mid-21st century) | Period of assessment (End of the 21st century) | Baseline / Control | Energy type | Impact model used | Geo-graphical coverage | Number of individual result considered in the analysis | Source of funding |
|---|---|---|---|---|---|---|---|---|---|---|
| **48** | IPCC SRES A2 and B1 | Ensemble of biased-corrected general circulation model (GCM) output for 3 GCMs | 2031-2060 (2040s) | 2071-2100 (2080s) | 1971 2000 | Thermal | Use of a hydrological-water temperature modelling framework The methodology used to assess the impact of climate change induced daily water temperature and 195 river flow changes on the usable capacity of thermal electric power plants was based on: Koch, H., Vögele, S., Kaltofen, M. & Grünewald, U. Trends in water demand and water availability for power plants scenario analyses for the German capital Berlin. Climatic Change 110, 879-899 (2012). | Europe and USA | 0 | European Commission (FP6 and FP7) |
| **49** | IPCC SRES A1B | Two regional climate models available for Germany. One of these models is REMO, developed at the Max-Planck-Institut fuer Meteorologie (MPI). The second climate model is the CLM model developed by the consortium of BTU Cottbus, Forschungszentrum GKSS, and Potsdam-Institut fuer Klimafolgenforschung. Both models are operated at the MPI and capture dynamic processes in the atmosphere at several spatial scales and with different regional coverages | 2036-2065 | 2071-2100 | 1981-2010 | Solar, Wind | Solar:<br>The authors develop a model of PV power generation based on a) the change in global radiation and b) the averaging due to the distribution of orientations and the tilt angles of PV modules within a region.<br><br>Wind:<br>Use of an Enercon E40 wind turbine with a rated power of 500 kW, a cut-in wind speed of 2,5 m/s and a rated wind speed of 13,0 m/s. | Germany's Northwest Metropolitan Region | 14 | German Ministry for Education and Research |

| # | Emission scenario(s) used | Climate model(s)/projection(s) used | Period of assessment (Near term to mid-21st century) | Period of assessment (End of the 21st century) | Baseline / Control | Energy type | Impact model used | Geo-graphical coverage | Number of individual result considered in the analysis | Source of funding |
|---|---|---|---|---|---|---|---|---|---|---|
| **50** | The climate model estimates an average warming of 1.4°C, and an increased and more variable precipitation total | The climate-change scenario was a regional model 'nested' within the Global Circulation Model (GCM) developed by the Hadley Centre, Bracknell, Berkshire. (HadCM2) | 2031-2060 | | 1961-1990 | Hydro | A simple water-balance model was used which describes the water level in Lac des Dix as the product of inflows and outflows of water in a particular month, as well as water stored from the previous month. | Grande Dixence Hydro-Electricity Scheme,Valais, Switzerland | 1 | Not mentioned |

## Appendix C- Peer-reviewed articles included in the systematic review but excluded from the analysis

Results from the articles focusing on bioenergy, wave energy and electricity networks were not included in the analysis because of the limited and conflicting evidence base they provided. Only four articles examine the impacts of CV&C on electricity generation from bioenergy (# 4, 9, 45, 46). They model the yields of different bioenergy crops in future climate conditions. No consistent patterns of impacts of CV&C could be extrapolated from the results of these four articles.

Two articles focus on electricity generation from wave energy. The first article (#21) quantifies how changes in the mean wind speed (a proxy for climate change) influence electricity generation by a Wave Energy Converter (WEC) in Western Scotland (UK). Harrison and Wallace (2005) demonstrate that under fixed conditions, WEC generation changes by up to 800 MWh/year (42%) for a 20% wind change. The second article (Reeve, Chen et al. (2011); #38) assesses the impacts of CV&C on generation by the Wave Hub WEC in Cornwall (UK). Although generation is projected to decrease by 2-3% under the A1B and B1 emissions scenarios for 2061-2100, this could be mainly due to the low efficiency of generation from steeper waves by the examined WEC (Reeve, Chen et al. 2011).

A single article examines the impacts of CV&C on electricity networks (#29). McColl, Palin et al. (2012) first formalise the current relationships between five types of weather-related faults and weather, and then use climate projections from a Regional Climate Model (RCM) to quantitatively assess how fault frequency could change in the 2020s-2080s. Their results suggest that lightning and solar heat faults are likely to increase but snow, sleet and blizzard (SSB) faults are likely to decrease (McColl, Palin et al. 2012). There are uncertainties regarding future wind, gale and flooding related faults.

The two articles on wave energy and the one on energy networks do not provide sufficient evidence to enable the identification of consistent patterns of impacts of CV&C. They also have limited spatial foci and thus limited value from a European perspective. For these reasons they were excluded from further analysis.

**Appendix D- Impacts of Climate Variability and Change (CV&C) on hydro-, wind, thermal and solar electricity generation at sub-national scale**

Hydroelectricity generation

The reviewed articles contained sub-national scale projections in the United Kingdom (#7), Switzerland (#13, #16, #50), Italy (#1, #27, #28) and Greece (#2, #30) for the near term to mid-21$^{st}$ century, and in Norway (#8), Switzerland (#13, #42) and Greece (#30) for the end of the 21$^{st}$ century.

A catchment-scale assessment for the South East of Switzerland (#13 *(1 individual result)*) projects a decrease in annual hydroelectricity generation for the near term to mid-21$^{st}$ century and the same study (#13 *(1)*), together with an assessment for the South West of Switzerland (#42 *(1)*), both consistently project a decrease in annual hydroelectricity generation for the end of the 21$^{st}$ century.

Two sub-national assessments (#2 *(1)*, #30 *(1)*) project a decrease in annual hydroelectricity generation for Greece for the near term to mid-21$^{st}$ century and a single assessment (#30 *(1)*) projects an annual decrease in hydroelectricity generation also for the end of the 21$^{st}$ century.

The Aurland hydroelectric power plant in Norway (#8 *(1)*) is the only sub-national scale case where the projections consistently suggest an annual increase in hydroelectricity generation for the end of the 21$^{st}$ century.

Only four articles provide individual results on seasonal impacts of CV&C on hydroelectricity generation for the near term to mid-21$^{st}$ century (#7, #16, #27, #28). For the Plynlimon catchment (UK), hydroelectricity generation is projected to increase in winter and decrease in summer. However, these seasonal impacts cancel each other out, to leave no discernible projected annual impact for the near term to mid-21$^{st}$ century (#7 *(1)*).

For the Swiss and Italian Alps, for the near term to mid-21$^{st}$ century, most individual results project a decrease in hydroelectricity generation for summers (#16 *(3)*, (#27 *(1)*) the only exception being the Valle d'Aosta catchment in Italy for which no robust pattern could be found (#28 *(1)*). An increase of hydroelectricity generation is consistently projected for autumns for the Val d'Aosta (#16 *(1)*) and Toce (#16 *(1)*) catchments in Switzerland and for the Noce catchment in Italy (#27 *(1)*).

The only catchment scale seasonal assessment for the end of the 21$^{st}$ century projects a decrease in hydroelectricity generation for the Aurland hydroelectric power plant in western Norway in winter (#8 *(1)*) and an increase in hydroelectricity generation in spring, summer and autumn (#8 *(1,1,1 repectively)*)

Wind electricity generation

Sub-national assessments of impacts of CV&C on wind electricity generation are available for Germany (#25, #40), Croatia (#34), Portugal (#41) and Spain (#41) for the near term to mid-21st century and for Germany (#40) and the United Kingdom (#20) for the end of the 21st century. Northern and South Western Germany are projected to experience an increase in annual wind electricity generation for the near term to mid-21st century (#25 *(1)*, #40 *(1)*) and so are the North of Scotland (#20 *(1)*), the North (#20 *(1)*), Middle (including Wales, #20 *(1)*) and South (#20 *(1)*) of England, and the Eastern Mediterranean (#5 *(1)*) region over land for the end of the 21st century. But an annual decrease in wind electricity generation is predicted for South Germany (#25 *(1)*) for the near term to mid-21st century and South West Germany (i.e. Freiburg, #40 *(1)*), Northern Ireland (#20 *(1)*) and the Eastern Mediterranean region over the sea (#5 *(1)*) for the end of the 21st century.

Wind electricity generation is projected to increase in autumn and winter in North West Germany (i.e. Bremen Oldenburg) (#49 *(1, 1)*) and in summer on the coast of Croatia (#34 *(1)*), the Ebro Valley (Spain, #41 *(1)*) and Albacete (Spain, #41 *(1)*) for the near term to mid-21st century. It is also projected to increase in summer, autumn and winter for Southern Andalucia (Spain #41 *(1,1,1)*) for the near term to mid-21st century.

Wind electricity generation is projected to decrease in North West Germany in August and November (#49 *(1,1)*) and in Northern Portugal in spring and autumn (#41 *(1,1)*) for the near term to mid-21st century. It is also projected to decrease in the Oeste Region (Portugal, #41 (#41 *(1)*), Northern Galicia (Spain, #41 *(1)*), Burgos (Spain, #41 *(1)*), and Albacete (Spain, #41 *(1)*) in spring and in Southern Cataluna in autumn and winter for the near term to mid-21st century (Spain, #41 *(1, 1)*).

For the end of the 21st century, wind electricity generation is projected to increase in summer on the West coast of Norway (#23 *(1)*) and in Northern France (#23 *(1)*) and the Western part of Iberia (#44 *(1)*). It is also projected to increase from December to March in the North of England (#20 *(1)*), Mid-England and Wales (#20 *(1)*) and England (#20 *(1)*), and in winter on the North Coast of Wales (North Hoyle wind farm, #10 *(1)*), the South East coast of England (Kentish Flats wind farm, #10 *(1)*), and in Northern Ireland (#20 *(1)*) and Western Germany (#23 *(1)*). Finally, wind electricity generation is projected to increase in autumn and winter in North West Germany (Bremen Oldenburg, #49 *(1, 1)*) and in April and August in the Eastern Mediterranean region (#5 *(1)*).

Wind electricity generation is projected to decrease in the summers of the end of the 21st century in Northern England (#20 *(1)*), Mid-England and Wales (#20 *(1)*), England (#20 *(1)*), Northern Ireland (#20 *(1)*), on the North Coast of Wales (North Hoyle wind farm, #10 *(1)*), on the South East coast of England (Kentish Flats wind farm, #10 *(1)*), the Bay of Biscay (#23 *(1)*), the Thyrean Sea (Italy, #23 *(1)*) and in winters in Scotland (#20 *(1)*), the Po Valley (Italy, #23 *(1)*), Southern Mediterranean (#23 *(1)*), and Eastern Spain (#23 *(1)*). It is also projected to decrease in December, January and May in the Eastern Mediterranean region (#5 *(1,1,1)*).

Thermal electricity generation

Thermal electricity generation at the Ferrybridge Power Plant in the United Kingdom is projected to decrease annually (#31 *(1)*) in the near term to mid-21st century, and similar projections exist for the plants on the River Weser (Central North West Germany, #25 *(1)*) and the River Rhine (central Southwest Germany, #25 *(1)*).

Solar electricity generation

Annual solar electricity generation is projected to increase for the near term to mid-21st century and the end of the 21st century in Mid- and South Scotland, Northern Ireland, Northern, Mid- and Southern England and Wales (for the UKCP09 50% probability level, #6 *(1, 1, 1, 1, 1, 1)*) and Western Greece (#33 *(1)*). It is projected to increase for the end of the 21st century only in Northern Greece (#33 *(1)*), Western Greece and Thrace (#33 *(1)*) and in Crete and the Aegean Islands (#33 *(1)*).

A decrease in annual solar electricity generation is projected for the Attica and Thessaly regions (Greece) for the near term to mid-21st century (#33 *(1, 1)*) and the end of the 21st century (#33 *(1, 1)*) and for the Northern of Scotland for the end of the 21st century (for the UKCP09 50% probability level, #6 *(1)*).

Seasonal impacts of CV&C on solar electricty generation were assessed in only one article, which projects an increase in solar eletricity generation in summers in North West Germany (Bremen Oldenburg, #49 *(1)*) and a decrease in winters (#49 *(1)*) for both the near term to mid-21st century and the end of the 21st century.