Energy 109 (2016) 1148–1159

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Review

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

Muriel C. Bonjean Stanton*, Suraje Dessai [1], Jouni Paavola [1]

Sustainability Research Institute and ESRC Centre for Climate Change Economics and Policy, School of Earth and Environment, University of Leeds, Leeds LS2 9JT, United Kingdom

ARTICLE INFO

Article history:
Received 24 February 2016
Received in revised form
3 May 2016
Accepted 4 May 2016

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

ABSTRACT

Understanding the impacts of CV&C[2] (climate variability and change) 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[3] (NT-MC) and the end of the 21st century[4] (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.

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1. Introduction

Devastating consequences of extreme weather are repeatedly making the front pages of the media across Europe, as they

* Corresponding author. Tel.: +44 (0)113 343 2846; fax: +44 113 343 5259.
E-mail address: M.C.BonjeanStanton13@leeds.ac.uk (M.C. Bonjean Stanton).
[1] Tel.: +44 (0)113 343 2846.
[2] CV&C: Climate Variability and Change.
[3] NT-MC: Near term to mid-21st century.
[4] EC: End of the 21st century.

http://dx.doi.org/10.1016/j.energy.2016.05.015

challenge the provision and security of critical services (e.g. Refs. [3,4,21]). Understanding the impacts of CV&C (climate variability and change) on electricity systems[5] 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 [9,14], the impacts of CV&C on the electricity systems have received less attention and regional, national and local assessments are still rare [10].

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 [37] examine the impacts of CV&C on demand and supply in the electricity markets whilst Rübbelke and Vögele [44,45] investigate the impacts of global warming on trade in electricity between European countries and on national electricity prices. Schaeffer et al. [46] 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 et al. [29], 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 et al. [2] 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. Only the articles from this latter strand of literature were selected for the review as the assessment approaches they use are more homogeneous and as such their results can be more consistently put in the context of each others'. The systematic review approach was used in order to collate, evaluate and interpret all the results of such research.

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 2 describes the method used in the systematic review and the data. Section 3 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 SLR (systematic literature review, see Ref. [5]). A literature review is "systematic" when it is based on a clearly formulated question, identifies relevant studies, appraises their quality and summarises their evidence [28]. 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 [40].

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 [6].

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 Ref. [27]) and ii) at least 12 models out of 15 agree on the sign of change" [47]. In this SLR we use Lloyd [32] 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 four successive steps: 1) search for peer-reviewed articles in Scopus using different keyword combinations; 2) high-level screening of the returned articles by applying four inclusion criteria; 3) further screening of the retained articles using a star-rating scorecard; and 4) collation and analysis of the results from the subset of included articles.

Scopus was chosen over WoS (Web of Science) 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 [15] 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 [8]. Then, 734 searches were run in Scopus using the improved keyword combinations. The searches yielded a total of 24,463 articles (including duplicates). Once imported into the EndNote software, the articles were first screened using four high-

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