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Review

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 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.

Contents

1. Introduction

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

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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.

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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.

level inclusion criteria and only the articles complying with all of these criteria were retained. These four criteria specified that articles needed to be 1) with European coverage (as defined by the United Nations Statistics Division) and 2) in peer-reviewed journal and 3) in English and 4) focusing on the impacts of CV&C on electricity generation and networks in the near-, medium- and long-term (no reviews).

Following Porter et al. [40], the retained articles (n = 57) were then 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. Refs. [19,35]; 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 Table 1). Their publication dates range from 1997 to 2015: there are more publications for years 2012 and onwards compared to the earlier years (Fig. 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%).

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-21st century and the end of the 21st century. Near term to mid-21st century (NT-MC) covers the period from the present until 2070, while the end of the 21st century (EC) covers the period from 2061 until 2100. There were 22 articles covering near term to mid-21st century and 10 articles covering the end of the 21st century. Both periods were covered by 11 articles. These periods were chosen for NT-MC and EC assessments as the earliest and latest assessment years across the subset of studies are respectively 2008 and 2070 for the NT-MC and 2061 and 2100 for the EC.

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 Ref. [31]), a figure (e.g. Fig. 4 in Ref. [12]) or in the text (e.g. Ref. [1]). Some articles have several individual results (e.g. Ref. [48]) whereas others only have a single one (e.g. Ref. [1] (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-21st century or the end of the 21st 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. Additionally, articles focusing on thermal electricity generation produced from fossil fuels, gas, biomass or nuclear energy were grouped as thermal electricity generation. CV&C is projected to affect the generation cycle efficiency and cooling water requirements of thermal power plants. Some divergences of opinions do exist however as to the water cooling quantities required by different thermal electricity generation technologies. For example Goldstein and Smith [22] and Delgado Martín [13] show that water requirements differ by fuel source, plant and cooling system type whereas World Nuclear Association [49] point out that: “there is no

Table 1
Data included in this study.

Identifier (#)	Paper 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 s ystem." 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 r egional 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.
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.
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(continued on next page)

Table 1 (*continued*)

Identifier (#)	Paper reference
	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.

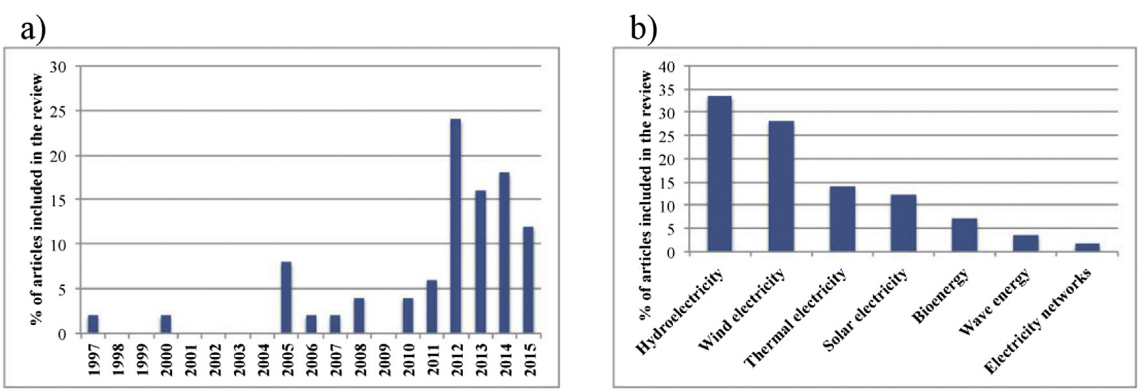

Fig. 1. Retained articles by publication year (a) and by electricity system focus (b).

real difference in the amount of water used for cooling nuclear power plants, relative to coal-fired plants of the same size". The different thermal electricity generation technologies covered in the articles retained for analysis had to be grouped together for the following reasons. Only 14% of the data (8 articles) reported results on thermal electricity. The majority (5) of these articles did not report results separately for nuclear and non-nuclear thermal generation. One article focus on nuclear generation only (#24) and another one on coal fired generation only (#31). Thus the separation of the results by thermal electricity generation technology was not possible. This is a gap in research, considering the importance of understanding the potential differences in the climate change impacts on thermal generation technologies. Furthermore, 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 1) combining emissions scenario(s) and climate model(s)/projection(s) (e.g. #2, #13, #27, #43) or 2) by rearranging observed time series with respect to a given linear trend for a selected variable (e.g. STARS[6] 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[7]) 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.

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 [46]. The impacts of CV&C on hydroelectricity generation are assessed using hydrological models (e.g. rainfall-runoff models such as IHACRES, TOPKAPI[8] or HBV Model,[9] GEOTRANSF[10]) or models simulating hydroelectric power plant operations.

Energy contained in wind is proportional to the cube of the wind speed [41] and thus variations in wind speed can have significant effects on generation. Schaeffer et al. [46] 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 (General Circulation Model) 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 [46]. Reliability of supply can also be threatened by water abstraction and regulations on discharge water temperature [38]. Water use models (e.g. WaterGAP3[11]), eco-hydrological models (e.g. SWIM[12]), 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 PV (photovoltaic) cell's efficiency and reduce generation [39], but also negatively affect temperature-sensitive CSP (concentrated solar power) 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. 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. Ref. [25]) 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 et al. [31] do consider both run-off-the-river and reservoir solutions for hydroelectricity generation, Crook et al. [12] include in their analysis the two most widely installed solar technologies for large-scale electricity generation, namely PV (photovoltaic) and CSP (concentrated solar power) and Van Vliet et al. [48] 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-21st century and EC: end of the 21st 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

Fig. 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.

3.2.1.1. Hydroelectricity generation. 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*

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[6] STARS or STatistical Analogue Resampling Scheme (From: https://www.pik-potsdam.de/research/climate-impacts-and-vulnerabilities/models/stars [Accessed 09/02/2016]).

[7] 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]).

[8] TOPKAPI or TOPographic Kinematic APproximation and Integration (From: http://www.progea.net/prodotti.php?p=TOPKAPI&lin=inglese [Accessed: 07/12/2015]).

[9] HBV Model (From: http://www.geo.uzh.ch/en/units/h2k/services/hbv-model/ [Accessed 07/12/2015]).

[10] Majone, B., A. Bertagnoli, A. Bellin and A. Rinaldo (2005) [34]. GEOTRANSF: a continuous non-linear hydrological model. AGU Fall Meeting Abstracts.

[11] Water Global Assessment and Prognosis or WaterGAP (Eisner, S. and M. Flörke (2015) [16]. Benchmarking the WaterGAP3 global hydrology model in reproducing streamflow characteristics. EGU General Assembly Conference Abstracts.

[12] 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]).

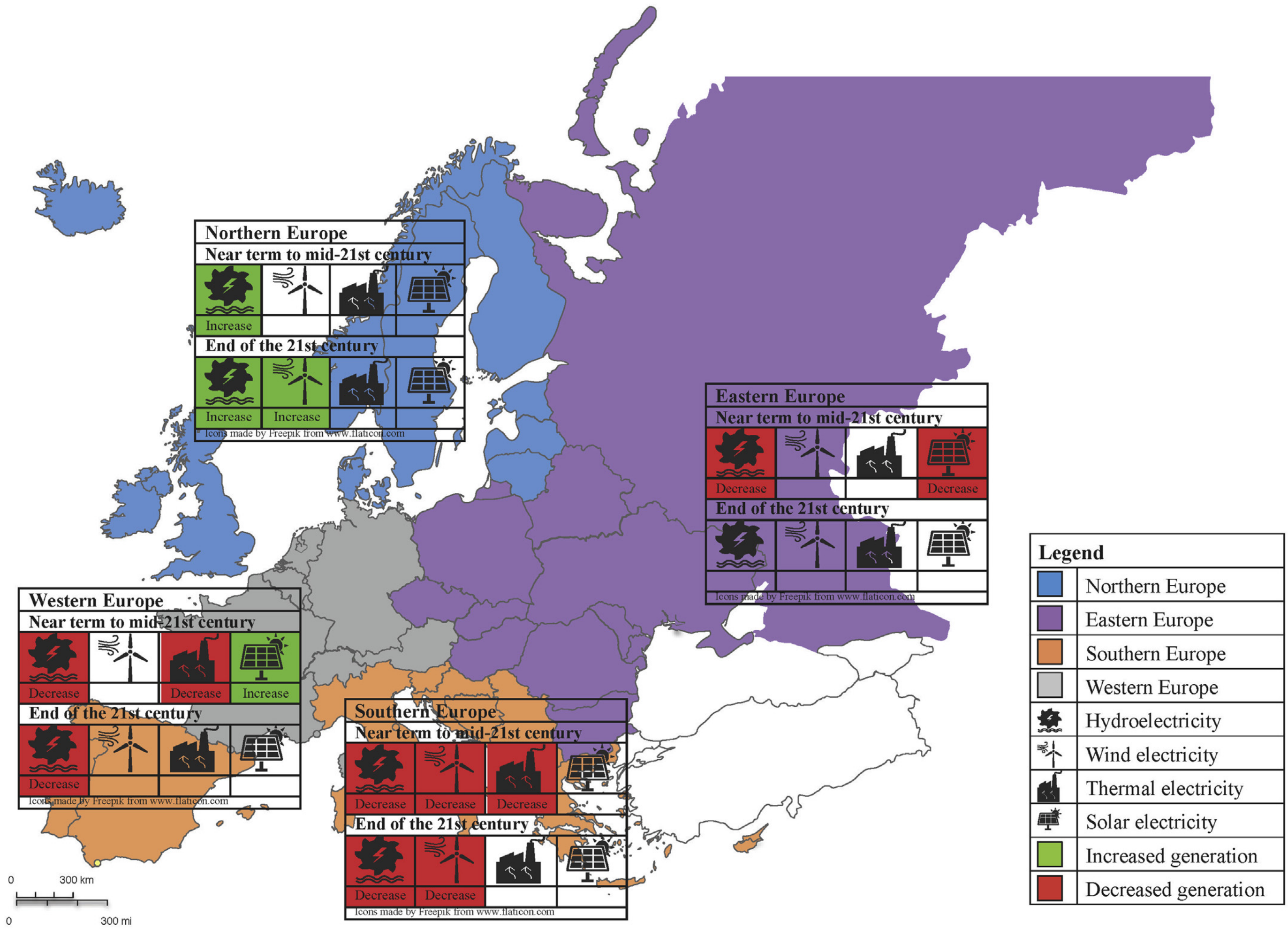

Fig. 2. Annual consistent patterns of impacts of CV&C on hydro, wind, thermo and solar electricity across the four European regions.

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-21st century and by the end of the 21st century. In Eastern Europe, hydroelectricity generation will decrease in the near term to mid-21st 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 21st century.

3.2.1.2. 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-21st 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 21st century. For Southern Europe, wind electricity generation is predicted to decrease in the near term to mid-21st century and for the end of the 21st 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 21st 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-21st century and the end of the 21st century (*NT-MC: 2; EC: 2*).

3.2.1.3. Thermal electricity. Annual thermal electricity generation is projected to decrease in Southern Europe and Western Europe (*1*) for the near term to mid-21st century (*2*). This projection resonates with the projections for decreasing precipitation and higher air temperature leading to evapotranspiration for Southern Europe [30], thus reducing the volume of runoff available for use as cooling water. For Western Europe, changes in drought severity that in turn could affect the availability of water for cooling, have also been attributed to climate change [7].

3.2.1.4. 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-21st century (*1*).

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

Figs. 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-21st century and the end of the 21st century, respectively. The figures also indicate where no pattern could be identified.

Figs. 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-21st century and the end of the 21st century. More individual results are available for the near term to mid-21st century than for the end of the 21st century. There is more agreement between individual results for the end of the 21st

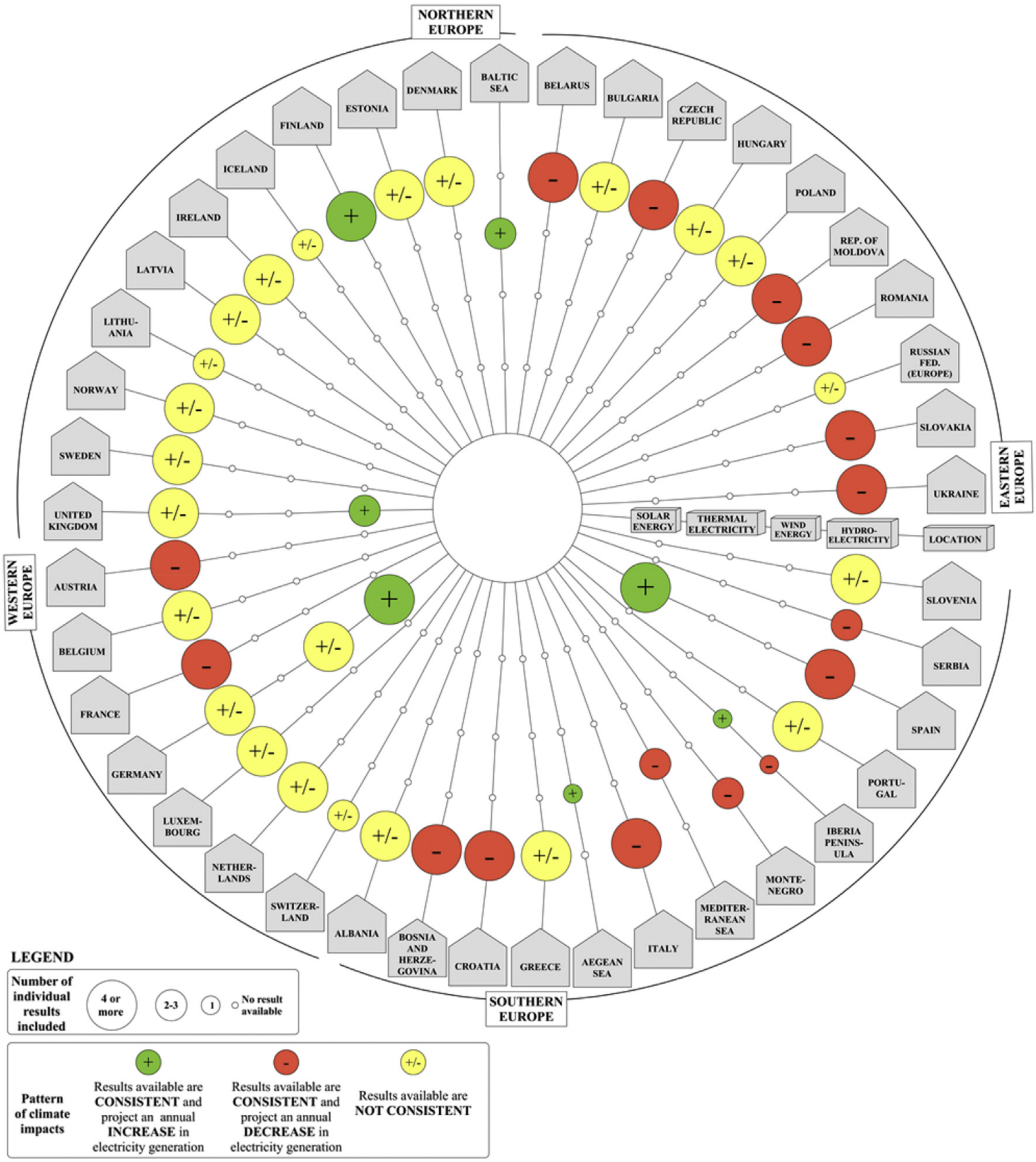

Fig. 3. Annual patterns of impacts of CV&C on hydro-, wind, thermal and solar electricity generation at national scale for the near term to mid-21st century.
Sources: Hydroelectricity: #25 (1 individual result), #26 (72), #34 (1), #35 (1), #43 (1) and #47 (70); Wind energy: #3(3), #44(2); Thermal electricity: #22(12), #24(1); Solar energy: #6(3), #11(8).

century than for the near term to mid-21st 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.

3.2.2.1. 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*),

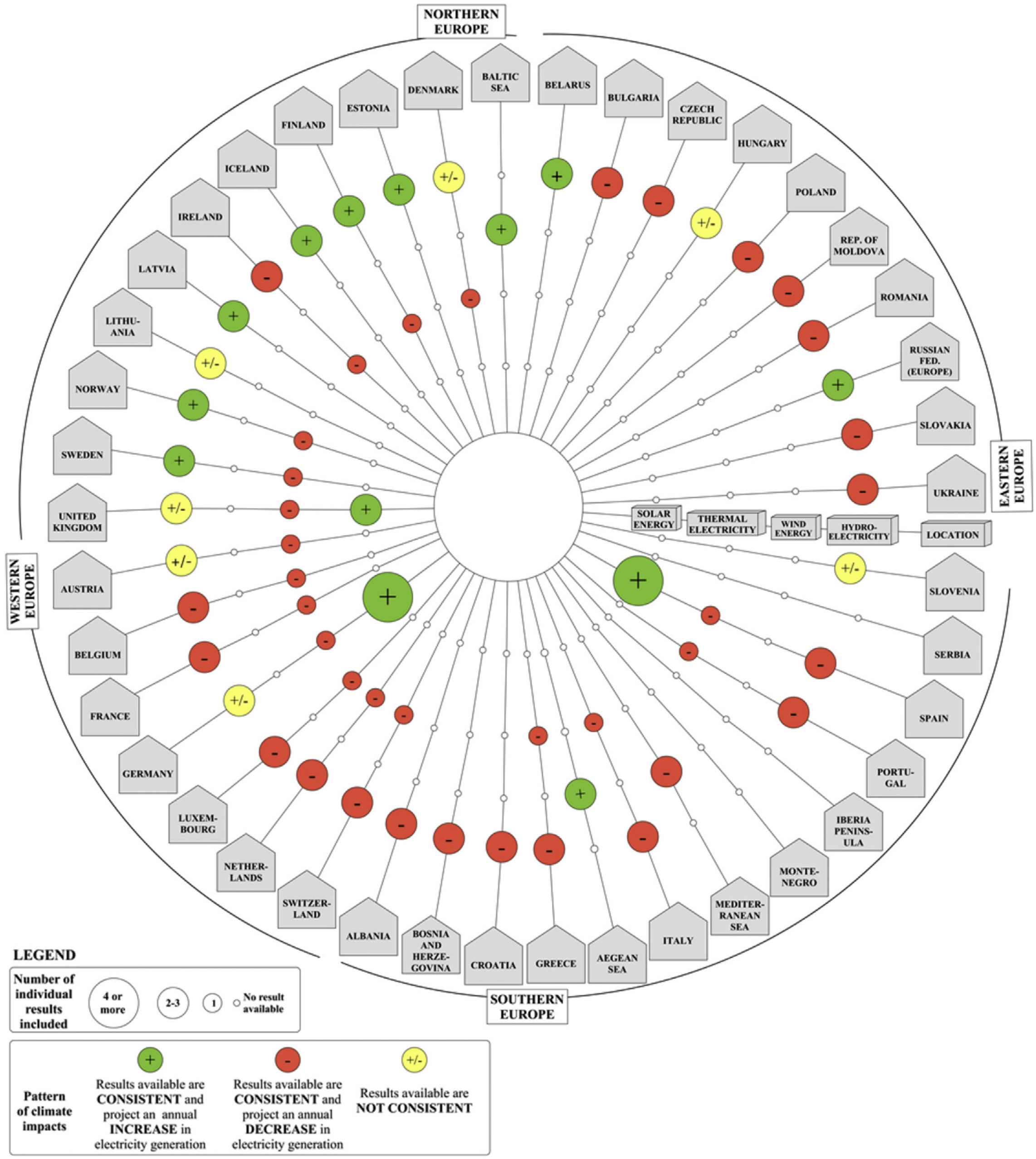

Fig. 4. Annual patterns of impacts of CV&C on hydro-, wind, thermal and solar electricity generation at national scale in the end of the 21st century.
Sources: Hydroelectricity: #17(16 individual results), #26 (72); Wind energy: #5(1), #23(1), #36(1), #44(3); Thermal electricity: #17(16); Solar energy: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

Greece (*3*), Italy (*3*), Portugal (*3*), Spain (*3*)).

3.2.2.2. Wind electricity generation. There is substantial uncertainty associated with assessing projected changes in wind [42]. 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*).

3.2.2.3. 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 OTC (once-through cooling) systems are consistently projected to experience a decrease in generation (*7*) but no consistent pattern of impacts can be identified for power plants with CCC (closed-circuit cooling) systems (*6*). All individual results project annual decrease in thermal electricity generation for the end of the 21st 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*)).

3.2.2.4. Solar electricity generation. Annual solar electricity generation is projected to increase for the United Kingdom, Germany and Spain for the near term to mid-21st century (*(3)*, *(4)*, *(4)*), and for the end of the 21st 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-21st century and the end of the 21st 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-21st century and end of the 21st century, for solar electricity in Germany in the near term to mid-21st century and in the United Kingdom and Spain in the near term to mid-21st century and end of the 21st century, and for wind electricity in the Iberian Peninsula in the near term to mid-21st century and over the Baltic and Aegean Sea in the near term to mid-21st century and end of the 21st 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 [27]. 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) [30]. 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 (Figs. 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 (greenhouse gas) emissions from 1990 levels by 40% by 2030 and by 80–95% by 2050, to retain global warming below 2 °C [17]. It would also help achieving the binding EU target of covering at least 27% of the European energy consumption from renewable sources by 2030 [18].

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. Ref. [20]) 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[13] 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-21st century impacts and fewer articles cover end of the 21st century impacts (Figs. 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 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[14]). Furthermore, future assessments should communicate uncertainties and confidence in the results more explicitly [33]. For example, the latest IPCC AR5 report uses two metrics for

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

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

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 [26].

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. Interdependencies assessments (e.g. Ref. [23]) could further the findings from this review by exploring how the impacts of CV&C on electricity systems could have knock-on effects on other sectors such as transport and water, other stakeholders such as consumers or policy-makers or national economies. 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 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 an early 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. Refs. [10,11]). 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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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.energy.2016.05.015.

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