Vulnerabilities and resilience of European power generation to 1.5 °C, 2 °C and 3 °C warming

Isabelle Tobin, W Greuell, Sonia Jerez, F Ludwig, R Vautard, Michelle T H van Vliet, Francois-Marie Breon

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LETTER

Vulnerabilities and resilience of European power generation to 1.5 °C, 2 °C and 3 °C warming

I Tobin[1], W Greuell[3], S Jerez[2], F Ludwig[3], R Vautard[1,4], M T H van Vliet[3] and F-M Bréon[1]

[1] Laboratoire des Sciences du Climat et de l'Environnement, IPSL, CEA/CNRS/UVSQ, Gif sur Yvette, France
[2] Department of Physics, University of Murcia, 30100 Murcia, Spain
[3] Water Systems and Global Change group, Wageningen University, Wageningen, The Netherlands
[4] Author to whom any correspondence should be addressed.

E-mail: robert.vautard@lsce.ipsl.fr

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Abstract

The electricity sector is currently considered mainly on the emission side of the climate change equation. In order to limit climate warming to below 2 °C, or even 1.5 °C, it must undergo a rapid transition towards carbon neutral production by the mid-century. Simultaneously, electricity generating technologies will be vulnerable to climate change. Here, we assess the impacts of climate change on wind, solar photovoltaic, hydro and thermoelectric power generation in Europe using a consistent modelling approach across the different technologies. We compare the impacts for different global warming scenarios: +1.5 °C, +2 °C and +3 °C. Results show that climate change has negative impacts on electricity production in most countries and for most technologies. Such impacts remain limited for a 1.5 °C warming, and roughly double for a 3 °C warming. Impacts are relatively limited for solar photovoltaic and wind power potential which may reduce up to 10%, while hydropower and thermoelectric generation may decrease by up to 20%. Generally, impacts are more severe in southern Europe than in northern Europe, inducing inequity between EU countries. We show that a higher share of renewables could reduce the vulnerability of power generation to climate change, although the variability of wind and solar PV production remains a significant challenge.

1. Introduction

The electricity sector is not only a major contributor to global warming, responsible for 25% of greenhouse gas (GHG) emissions (IPCC WGIII 2014), but it will also be impacted by changes in climate through their effects on supply and demand. Changes in near-surface wind speed and cloudiness directly impact the amount of energy produced by wind and solar photovoltaic (PV) power farms (Pryor and Barthelmie 2010, Reyers *et al* 2015, Tobin *et al* 2016, Crook *et al* 2011, Jerez *et al* 2015a). Hydropower is vulnerable to reduced river flows induced by decreases in precipitation and increases in evapotranspiration (van Vliet *et al* 2013, 2016a, Lehner *et al* 2005). The potential for cooling water uses will also become more critical due to river flow reductions combined with water temperature increases, which will affect the usable capacity of thermoelectric power plants (van Vliet *et al* 2012a, 2016a). On the demand side, heating and cooling-related power demand is sensitive to changes in air temperature (Damm *et al* 2017). In particular, extreme events such as heat waves and droughts (e.g. the summer of 2003 in Europe) will have a substantial impact on both supply and demand of electricity (IAEA 2004, van Vliet *et al* 2016a).

The above studies along with others (e.g. Miara *et al* 2017, Karnauskas *et al* 2017) have comprehensively examined climate change impacts on various aspects of the power sector. Limited work, however, has been done to assess the combined vulnerabilities of different power-generating technologies in a consistent way, using the same assumptions and climate model experiments. Previous independent energy studies are based on different sets of global climate model (GCM) or regional climate model (RCM) simulations, different emission scenarios and different time horizons (mid-century vs. end of century). This heterogeneity

Table 1. Overview of selected RCM model experiments and time horizons for 1.5 °C, 2 °C and 3 °C warming limits.

RCM	Driving DCM	Scenario	1.5 °C	2 °C	1.5 °C
CSC-REMO	MPI-ESM-LR-r1	RCP8.5	2014–2043	2030–2059	2053–2082
SMHI-RCA4	HadGEM2-ES-r1	RCP8.5	2004–2033	2016–2045	2037–2066
KNMI-RACMO22E	EC-EARTH-r1	RCP8.5	2012–2041	2028–2057	2052–2081
SMHI-RCA4	EC-EARTH-r12	RCP8.5	2012–2041	2027–2056	2052–2081
SMHI-RCA4	HadGEM2 E S-r1	RCP4.5	2007–2036	2023–2052	2055–2084

limits the possibility of a consistent assessment of the electricity sector's vulnerabilities and complicates the use of this information for decision making by stakeholders. Assessing these various effects of climate change in a consistent way is necessary for energy companies and policy makers to develop adaptation measures and to ensure future energy security.

Here, we assess climate change impacts on four electricity supply technologies (wind, solar, hydro and thermal power supply) using a consistent approach. Climate change impacts on wind power, PV power, hydropower and thermal power are considered for 28 European Union countries based on a common five-member ensemble of state-of-the-art regional climate model projections (EUROCORDEX, Jacob *et al* 2014). The reference (1971–2000) and future time periods considered are the same for each technology. As guidelines and objectives for climate-energy policies are often expressed in terms of their level of global warming limitation, our assessment focusses on three levels of global warming above preindustrial levels, i.e. 1.5 °C, 2 °C and 3 °C, that occur at different times among simulations, rather than fixed future time periods. The first two levels are in line with the targets achieved in the COP21 Paris agreement, while the third one is the most likely level given the current national voluntary contributions for GHG emission reduction. Consistent impact assessment for those three levels of global warming will enable one to weigh emission reduction efforts with gains and losses in terms of power generation. Such assessments should facilitate the uptake of climate change impact information by policy makers.

2. Climate and energy models and simulations

2.1. Climate model simulations

Five regional climate model simulations from the EUROCORDEX initiative (Vautard *et al* 2013, Jacob *et al* 2014) are used here to assess climate change impacts on the four different sub-energy sectors (i.e. wind power, solar PV, hydropower and thermoelectric power). This ensemble of simulations is based on combinations of three GCMs and three RCMs (table 1). In order to keep the number of models low, a model selection methodology was used following the approach of Mendlik and Gobiet (2016). This sub-ensemble selection, made among a larger simulations set, was imposed for a broader context of evaluation of cross-sectoral impacts within the FP7 IMPACT2C Project (www.impact2c.eu), where impacts could not be calculated for all possible simulations due to the computational burden. Four simulations are forced with an RCP8.5 radiation forcing scenario, and one is forced with an RCP4.5 scenario. The climate warming periods (1.5 °C, 2° C and 3 °C) were selected for each simulation using the methodology described in Vautard *et al* (2014). The time windows are defined as the earliest 30-year periods with time-averaged global mean temperature increase, as projected by the RCM-driving GCM simulation, equal to 1.5 °C, 2 °C, 3 °C warming, respectively, compared to the 'pre-industrial' period 1881–1910. The limit of 1.5 °C is reached over periods spanning 2004–2043 for the ensemble, 2 °C over 2016–2059 and 3 °C over 2037–2084. The reference climate period used to compare future changes in power generation was decided to be 1971–2000 in all IMPACT2C project studies, in particular because it is included in the CMIP5 historical period.

The spatial resolution of these simulations is 0.11° in latitude and longitude, i.e. about 12 km over the European domain. For wind and solar PV analyses we retrieved three-hourly data of the relevant variables (described in the here below subsections) from the climate simulations while daily time-series were used for hydropower and thermoelectric power.

The recent past climatology of these simulated climate variables relevant for the four sub-sectors have already been evaluated against observational data in previous studies (Tobin *et al* 2016 for wind speed, Jerez *et al* 2015a for solar radiation, temperature, wind speed, Casanueva *et al* 2015, and Prein *et al* 2016 for precipitation, and Vautard *et al* 2013 for summer temperatures and heat waves critical to thermoelectric power). Daily model outputs of temperature, precipitation, radiation and wind speed were bias-corrected to be used as input for the hydrological and water temperature models. Raw outputs were used for three-hourly wind and solar PV power. For wind power, the order of magnitude of relative changes in wind power assessed from raw output have been shown to be similar to those assessed from bias-corrected output in a previous study (Tobin *et al* 2015). For solar PV we just adopted the same approach (i.e. the use of model raw data) as in previous studies (Crook *et al* 2011, Jerez *et al* 2015a).

2.2. Wind power

To assess climate change impacts on the European wind power sector, we calculate future changes in wind power production from the wind farms installed as of 2013 over 26 countries (most EU countries, and the United Kingdom and Switzerland) between each of the three future periods and the reference period. Wind power production is computed following the methodology described in Tobin *et al* (2016).

As the wind speed at the turbine height is not stored as a standard model output in climate projections, wind speed at 10 m (U_{10}) has to be first extrapolated vertically to the turbine hub height (H) using the power law first established by Elliott (1979), $U_H = (U_{10})^{1/7}$. Then, wind speed at the turbine hub height (U_H) is converted into turbine-generated electric power (P) using a standard power curve (see supplementary material, I-1 available at stacks.iop.org/ERL/13/044024/mmedia). Information on the location, installed power capacity and hub height of 2013 wind turbines is taken from thewindpower.net database (www.thewindpower.net).

We use the current wind farm distribution to assess future relative changes in wind power potential, even though a large increase in wind capacity is expected. This assumption was shown to lead to impacts with similar orders of magnitude as the future wind installations scenario (Tobin *et al* 2015, 2016).

2.3. Solar PV power

To assess climate change impacts on PV power, we calculate future changes in PV power production, based on the installed capacity in 2012, between each of the three future periods and the reference period. The methodology developed in Jerez *et al* (2015a) is followed here to compute PV power production using the spatial distribution of the 2012 PV power installations derived from the CLIMIX model in Jerez *et al* (2015b).

The PV power generation potential (PVpot) is calculated at the grid cell level using the three-hourly downwelling solar radiation, together with the near surface air temperature and wind speed, which impact the PV cells' efficiency (the latter decreases as the solar cell temperature increases) (Radziemska 2003). To calculate PV power production at the national scale, PVpot is used to compute PV power production according to the PV power installed capacity in each grid cell (as established in Jerez *et al* 2015b), considering no-tilted PV panels. Then PV power production is aggregated over the locations of the PV plants of each country.

2.4. Hydropower

Climate change impacts on hydropower were quantified by focussing on changes in gross hydropower potential i.e. 'the annual energy potentially available when all natural runoff in a country is harnessed' (Eurelectric 1997). This quantity has shown to be a good indicator for assessing relative changes in actual hydropower potential (Lehner *et al* 2005, van Vliet *et al* 2013, 2016b).

The VIC hydrological model (Liang *et al* 1994, Lohmann *et al* 1998) was used to produce daily streamflow projections on 0.5° × 0.5° spatial resolution for Europe. The VIC hydrological model was applied using the elevation and land cover classification as described in Nijssen *et al* (2001) and using the DDM30 routing network (Döll and Lehner 2002) The climate output variables from the CORDEX simulations that are used as input for the VIC hydrological model are daily values of precipitation, minimum and maximum temperature, incoming fluxes of short- and long-wave radiation, humidity and wind speed. The first five of these variables are bias-corrected using the quantile mapping method. The gross hydropower potential is estimated at each 'river grid cell' using simulated streamflow and information on flow direction (which cell receives the water from the considered cell) along with elevation differences between the cell and the cell receiving water.

2.5. Thermoelectric power

Streamflow and water temperature projections were produced on daily time step and 0.5° × 0.5° spatial resolution for Europe with the VIC hydrological model and RBM water temperature model (Yearsley 2009). RBM solves the 1D-heat advection equation using a mixed Eulerian–Lagrangian approach (Yearsley 2009, Yearsley 2012). RBM was previously modified for application on a worldwide level and to include the effects of heat effluents from thermoelectric power plants and reservoir impacts on water temperature (van Vliet *et al* 2012a, van Vliet *et al* 2012b). The VIC-RBM framework was validated for river basins in Europe and worldwide (van Vliet *et al* 2012a, van Vliet *et al* 2012b, 2016a) and these models were forced with (bias-corrected) output of minimum and maximum temperature, precipitation and wind speed from the RCMs to simulate streamflow and water temperature under future climate.

The impacts of changing streamflow and water temperature on thermoelectric power generation were quantified using the model of Koch and Vögele (2009), which was modified as described in van Vliet *et al* (2012a). This model simulates in a first step the required water demand for cooling and in a second step the usable power plant capacity. A distinction was made between thermoelectric power plants using once-through cooling and recirculation cooling (see supplementary information). The thermoelectric power production model was applied to 407 power plants in Europe which include nuclear, fossil- and biomass-fuelled power plants. For the description of power plant characteristics, we used the data of the World Electric Power Plant Database version 2013 (UDI 2013). We selected power plants according to the following main criteria: use of river water as source for cooling, availability of information on installed

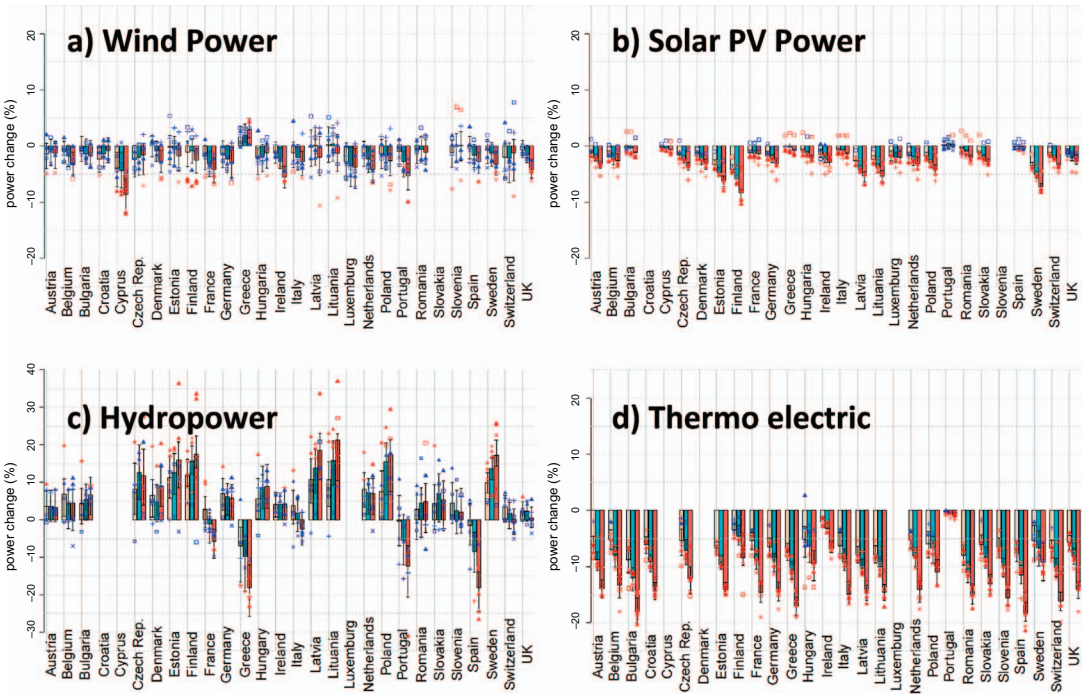

Figure 1. Future changes in national wind power (*a*), solar PV power (*b*), hydropower (*c*) and thermoelectric power (*d*) productions under +1.5 C global warming (grey bars), 2 °C (cyan bars) and 3 °C (salmon bars). Changes are relative to the reference period 1971–2000. Colored bars correspond to the ensemble mean. The black thin error bars represent ensemble-mean confidence intervals (95% level based on the Wilcoxon-Mann-Whitney test). Symbols indicate individual model changes and are red if individually significantly different from 0 at the 95% level (based on the Wilcoxon-Mann-Whitney test) and blue otherwise. The filled triangle symbol is repeated twice as it corresponds to both simulations produced from the same GCM-RCM chain but under different scenarios.

capacity and cooling system type (van Vliet *et al* 2016a). Thermoelectric power plants using sea water or groundwater as main source for cooling or using dry (air cooling) systems were excluded from the analyses. Considering the long design life of thermoelectric power (30–60 years) and a lack of detailed information on future power plant changes, we assumed that the power plant settings will remain constant in time.

The impact of climate change on the river flow and water temperature was first calculated for each thermal power plant by extracting the relevant data for the grid cell that contains it. The individual power plant results were then aggregated at the national scale.

3. Results

Overall reductions in wind power potential are projected (ensemble mean results) for all countries considered except Greece, where projected changes are positive (figure 1(*a*)). The magnitude of change is overall small ($< 5\%$) for all countries under a 1.5 °C and 2 °C global warming in terms of ensemble mean and are insignificant for most RCM experiments. For a 3 °C warming, most countries undergo changes with a magnitude also below 5% except for Portugal, Ireland and Cyprus where decreases in magnitudes are expected to exceed 5% (approaching 10% for Cyprus). A 2 °C warming does not systematically lead to higher change magnitudes than 1.5 °C, while 3 °C warming leads to stronger changes in most cases. In terms of individual climate model signals, the spread among the models is limited. Signals are within a 5% range with a spread in signs of changes among models. The more extreme signals of change from individual models remain within the range of 5%–12%. The strongest signals do not correspond to a single climate model. The model with the strongest signal is country dependent. Summarizing, overall small but statistically significant reductions in wind power potential are projected for most European countries.

For solar PV generation (figure 2(*b*)), projected ensemble mean impacts show moderate reductions for most countries, expect for Portugal, Spain, Greece and Cyprus where changes were very small. The magnitude of the ensemble mean changes are comparable with the wind power changes, less than 5% for all countries under the 1.5 °C and 2 °C global warming scenarios. Under 3 °C warming, most countries still undergo changes with a magnitude below 5%, except for the Baltic countries, Finland and Sweden where declines are stronger and expected to be within the 5%–10% range. The overall magnitude of the signals is correlated with the amount of warming: 3 °C warming results in the strongest changes and 1.5 °C warming the lowest changes.

Most models project significant changes (at the 95% confidence level), agreeing on the direction of changes (positive or negative), with the spread among models being very low. To summarize, the changes in

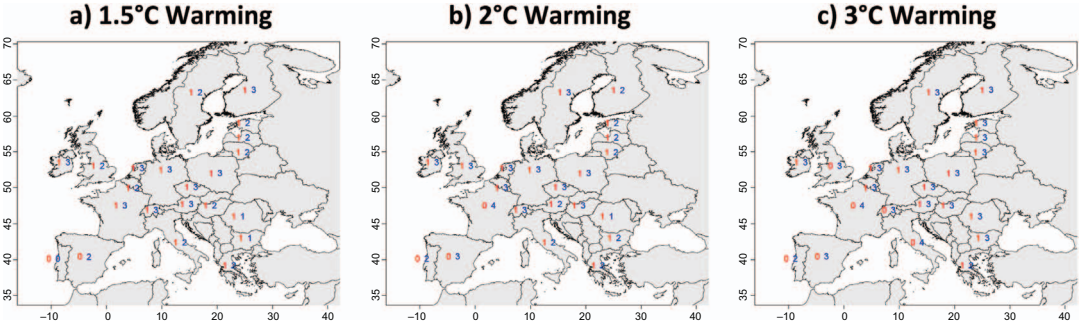

Figure 2. Red and blue figures indicate the number of power-generation sub-sectors impacted by climate change positively and negatively respectively. From left to right: 1.5 °C warming, 2 °C warming, and 3 °C warming.

solar PV are negative and modest for most countries (within 5%–10% at most, even considering the individual signals from each model) but the magnitude and direction of changes are robust since most models agree. The decreases in solar power are due to a decrease in downwelling shortwave radiation, likely linked to the increase of water vapour due to warming (Bartok *et al* 2016).

Mean gross hydropower potential increases in northern, eastern and western Europe and decreases in southern Europe (figure 1(*c*)). In 18 countries increases in hydropower potential are projected and for three countries reductions are found (Greece, Spain and Portugal). For four countries, including France and Italy, the changes depend on the level of warming where a 1.5 °C leads to an increase while a 3 °C warming results in a decrease in gross hydropower potential. The magnitudes of change of the ensemble mean do not exceed 10% for 1.5 °C, 15% for 2 °C or 20% for 3 °C. Overall, higher warming results in stronger changes. Results for the individual RCM projections show that many individual signals are not significant. A few models project significant changes of a magnitude that exceed 30%. Spread among models is substantial. The most negatively impacted countries will be Greece, Portugal, and Spain. Impacts in these southern European countries can be reduced by limiting global warming. A warming of 3 °C reduces hydropower potential by 15%–20% while limiting to 2 °C warming would keep decreases below 10%. Under a 1.5 °C warming scenario the ensemble mean indicates a reduction of 5% or less. The Baltic and Scandinavian countries would be the most positively impacted (increase exceeding 15% under 3 °C as projected by the ensemble mean). However, substantial uncertainty is associated with these results due to a large spread between the climate models.

Due to a combination of higher water temperatures and reduced summer river flows, the usable capacity of thermoelectric power plants using river water for cooling is expected to reduce in all European countries (figure 1(*d*)). Increased global warming results in systematically larger impacts. The magnitude of the decreases are about 5% for 1.5 °C, 10% for 2 °C and ~15% for 3 °C for most countries. Bulgaria, Greece and Spain will be the most strongly impacted (15%–20% decrease). In terms of individual model signals, most models project significant changes and agree on the direction of changes as the spread among signals is limited. The spread of simulated changes is limited mainly because of the relatively small spread in simulated (water) temperature changes. Robust and significant negative climate change effects are found, with a magnitude higher than for other sub-energy sectors and concerning all European countries.

4. Synthesis analysis

In order to provide a qualitative and quantitative assessment of climate change impact on overall European power generation, a synthesis analysis is conducted using the results from individual power generation sub-sectors. This is done in two ways.

First, a qualitative assessment is simply provided by counting the number of power-generating sectors positively and negatively impacted for each country. A sub-sector is considered impacted (negatively or positively) by global warming when the magnitude of change of production or production potential exceeds or equals 1% (as projected by the ensemble mean). Power generation undergoes negative impacts in all European countries included in this assessment and under all global warming assumptions (except for Portugal, where all sectors exhibit no change under 1.5 °C) (figure 2). Twenty (out of 22) countries have only one (out of four) sub-sectors positively impacted under 1.5 °C, 19 under 2 °C, 16 under 3 °C, and no country has more than one sub-sector positively impacted in any scenario. On the contrary, all countries have at least one sub-sector negatively impacted under all warming scenarios (except for Portugal under 1.5 °C). Under 3 °C warming, 20 countries have at least three sub-sectors undergoing negative impacts against 12 and eight countries under 2 °C and 1.5 °C respectively. The number of negatively impacted subsectors then increases with warming.

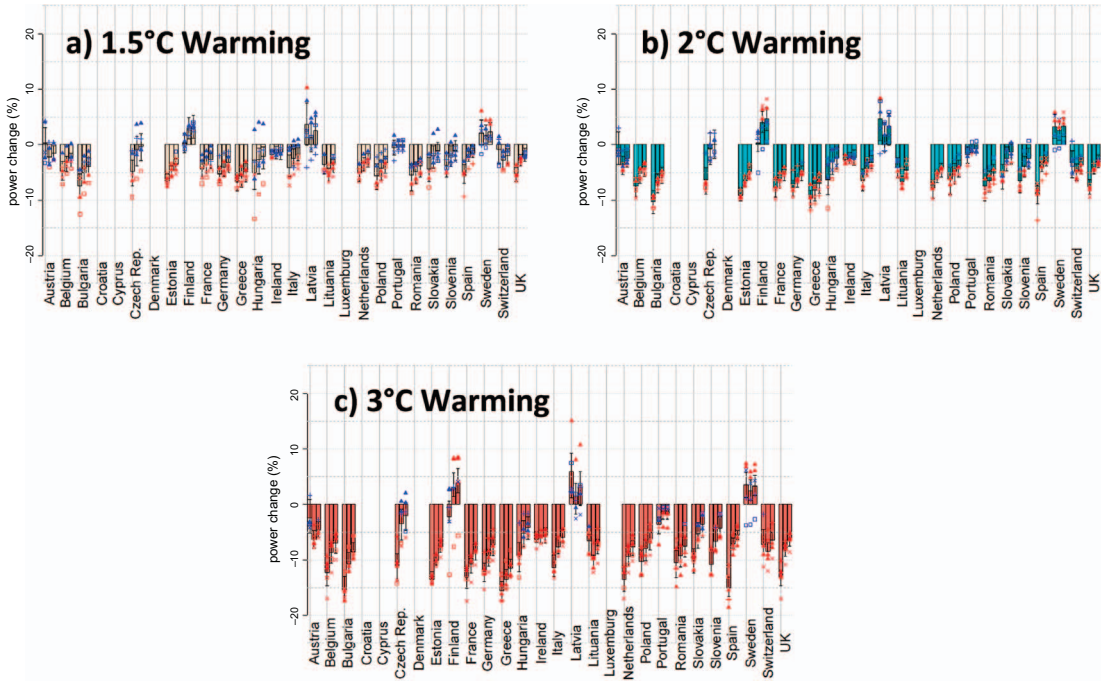

Figure 3. Changes in overall power generation for different power mixes (per country, left bar = baseline; middle bar = 60% RES; right bar = 80% RES); (*a*) 1.5 °C warming; (*b*) 2 °C warming; (*c*) 3 °C warming. Changes are relative to the reference period 1971–2000. Colored bars correspond to the ensemble mean. The black thin error bars represent ensemble-mean confidence intervals (95% level based on the Wilcoxon-Mann-Whitney test). Symbols indicate individual model changes and are red if individually significantly different from 0 at the 95% level (based on the Wilcoxon-Mann-Whitney test) and blue otherwise. The filled triangle symbol is repeated twice as it corresponds to both simulations produced from the same GCM-RCM chain but under different scenarios.

Second, a synthesis is made by weighting the production changes in each country by future mix assumptions. This allows a more quantitative assessment of integrated impacts in European electricity generation potential. We used estimated baseline (2012) mixes (Observ'ER 2013) and potential mixes including a 60% and 80% penetration of renewables (60%RES and 80%RES respectively). These mixes were proposed by the European Climate Foundation (European Climate Foundation 2010), and numbers can be found in the supplementary information. These mixes are to be taken as illustrative, as other possibilities with different spatial distributions and shares exist for the same penetration. Also, assumptions are made, for instance that all thermoelectric power production is from plants using river water for cooling, which needs to be kept in mind for interpreting the results. Figure 3 shows the changes obtained for different global warming temperatures. For the baseline mix, the overall impact is negative everywhere except in Scandinavian countries and Latvia, and impact amplitudes increase with the warming level. The positive impacts experienced by Scandinavian countries and Latvia are explained by the substantial hydropower share in the baseline power mix in association with positive impacts on this subsector. For a 1.5 °C warming, impacts remain limited and generally below 5%, except for a few countries (Estonia, Greece, Poland, Romania and Spain). For a 3 °C warming, impacts are higher and reach about a 15% reduction in potential in southern European countries.

Interestingly, impact amplitudes are sensitive to the contribution of renewable energy resources (RES). The higher the renewable share, the lower the impacts, except in a few countries. For a 3 °C scenario, for many countries, the 80% RES contribution reduces the overall impact by a factor of 1.5 or more. The largest mitigation is for Spain, where negative impacts on power potential reduce from a 15% decrease for the current mix to a 5% decrease for a high RES penetration (80%). This is due to the large current share of thermoelectric power, which is the most sensitive to climate change (see figure 1(*c*)) due to combined streamflow and water temperature impacts. Therefore, the penetration of renewable energies should make the overall production potential less vulnerable to climate change, but the assumption that all thermoelectric production is using river water induces a probable overestimation of this effect, as power plants using sea water or dry (air) cooling are probably less sensitive to climate change.

5. Discussion and conclusions

Our results highlight several aspects of the vulnerability of electricity production in Europe. We focused on understanding the impacts of climate change for given levels of warming using a limited number (five)

of climate model simulations, inducing some uncertainty. However, results are in line with previous studies for all technologies considered.

The work presented here is not aimed at an accurate quantitative assessment of climate change effects on actual future power generation for each sub-sector, as current fleets are used and no change in the spatial distribution is accounted for in the analysis. For hydropower, a gross hydropower potential quantity is used to conduct the analysis. Also, for thermoelectric power, the assessment is restricted to current power plants for which the required information was available and we focused only on plants using river water as the main source for cooling. These limitations lead to uncertainties, so results should be taken in a qualitative way. Also, climate data are not bias-corrected for wind power and PV while they are for hydropower and thermoelectric power. However, previous studies have shown that relative effects are only marginally sensitive to bias-correction, at least for wind power; see Tobin *et al* (2015). Thus we argue that despite the limitations of this study, the orders of magnitude are relevant and reliable.

We have assessed mean changes in electricity production from technologies. Climate change is also known for affecting changes in the variability of some climate variables, such as temperature. However, previous studies have not detected major changes in the variability of wind and solar PV energy production (Tobin *et al* 2016, Jerez *et al* 2015a). Previous work has shown that climate variability and extremes have important impacts, particularly on thermoelectric power usable capacity, and to a lesser extent also on hydropower usable capacity (van Vliet *et al* 2012a, van Vliet *et al* 2016b). In our study, the thermoelectric power model simulations were initially performed on a daily level before aggregating to mean annual level, including the impacts of daily variability on the mean changes.

Our results show the need for climate change adaption, in particular for the thermoelectric power and hydropower sectors in Europe. Van Vliet *et al* (2016c) showed that combinations of various adaptation options (e.g. increased plant efficiencies, changes in cooling system types and fuel switching) might be an effective strategy in reducing the impacts of water constraints on hydropower and thermoelectric power supply.

Our results highlight the fact that climate change, regardless of the warming level, will negatively affect power generation in European countries regardless of the warming level. This conclusion qualitatively holds at the overall generation level, by assuming that all four sub-sectors (wind, PV, hydroelectric and thermoelectric power) in national power mixes have the same weight, or by weighting the results for each technology by their relative share in the mix. Most sub-sectors actually undergo negative impacts in central, western and southern regions, and each country has more negatively than positively impacted sectors. Above all, we demonstrated that it is, however, worth limiting global warming under 2 °C and even 1.5 °C as a significant amount of additional impacts can be avoided compared to a 3 °C global warming: for some countries, the impacts could be greater by up to a factor of two.

An important finding of this study is that southern Europe will generally be more strongly impacted than northern Europe. In particular, Spain and Portugal are most severely affected by climate change. This could induce inequity among EU countries without proper adaptation strategies, and when deciding upon future energy mixes, these climate change impacts should be addressed. Another one is that the two power-generating technologies that will be the least impacted by global warming are wind and PV power. The hydropower sub-sector will undergo positive as well as negative effects with magnitudes higher than for PV and wind power. Thermoelectric power plants using river water for cooling will undergo negative changes over all countries, with a magnitude that can be three times higher than for wind and PV power. Therefore, increasing the wind and PV power share in combination with reducing thermoelectric power (primarily fossil-fuel based power) in the European power mix will have a double benefit: contributing to climate change mitigation and making power generation less vulnerable to climate change. This conclusion does not, however, account for the increase in the lack of dispatchability of energy, due to the solar PV and wind energy increase, which would make the mix more vulnerable to climate and weather variability. This is an important challenge for ensuring balance between power generation and demand, along with grid stability, and this also raises power storage issues.

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ORCID iDs

R Vautard https://orcid.org/0000-0001-5544-9903

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