Final author comments: More Homogeneous Wind Conditions Under Strong Climate Change Decrease the Potential for Inter-State Balancing of Electricity in Europe

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Throughout this manuscript red denotes deletions from the original manuscript and green denotes additions to the text.

Reviewer 1

We thank the reviewer for his/her helpful comments to improve the manuscript. The points of criticism were clearly formulated and mostly straightforward to implement. We are confident that the modifications helped enhance the readability and avoid misinterpretations.

Minor Point 1

The captions of tables and figures are very long and include details on methods and even on findings. I found it useful actually, but captions should describe the figure or table, nothing more and nothing less. Maybe consult with the journal editors for guidance. You can easily move some of the caption text into the main text.

Author's response

This aspect has been repeatedly mentioned by both reviewers (see Reviewer 2, Minor Points 7,8). We hence decide to shorten captions where possible and move interpretations and discussion to the main text.

Changes in the manuscript

Caption of Fig. 1, p. 8:

> **Approach of the study.**
> **a)** Wind fields from high-resolution climate models and the 2010/2011 Net Transfer Capacities are used as input to the model. **b)** The wind speeds are first translated into generation of individual wind parks using local wind fields . In a second step the generation is and then aggregated to a national level for each country. **c)** In combination with country-specific load data, the nodal mismatch for every country and timestep is computed. If generation exceeds the load (green area), countries can export energy until lines reach their transmission capacity. Remaining energy has to be curtailed (dumped).

If generation is lower than load, electricity is imported. If importing is not an option due to transmission limits or lack of available excess energy in other countries, backup energy has to be provided by dispatchable power plants (e.g. gas turbines or other thermoelectric plants). **d)** We assume a controllable European power transmission grid. A minimization of the total backup energy of all countries then yields a flow pattern in Europe. In the shown case, strong winds over the North Sea lead to high generation in this region while there is little generation in the southern part of Europe. Energy is hence mainly transported from the North Sea region to Southern Europe and the high transmission needs lead to an operation of almost all lines at their maximum.

Caption of Table 1, p.9

see Reviewer 2, Minor Point 6

Caption of Fig. 2, p. 11:

The impact of climate change on backup energy under different grid expansion scenarios. Different realizations of the European inter-state grid expansion are given by the grid expansion coefficient α. While $\alpha = 0$ denotes the isolated case without inter-country transmission network, $\alpha = 1$ reproduces the configuration as of today and $\alpha = \infty$ represents unlimited European transmission. Different markers refer to distinct 20 year time periods (see Table 1), colors denote different climate models. **a)** Backup energy as a function of grid expansion expressed in units of the total European load $D_{\text{tot}} = \int \sum_i D_i(t)dt$. **b)** Absolute change of backup energy by the end of the century. **c)** Relative change of backup energy by the end of the century.

a) Backup energy decreases monotonously with grid expansion. Without any grid, approximately 45 % of the wind-energy is produced at the wrong time and thus has to be curtailed and backed up lateron. This number can be theoretically reduced to roughly 27% by grid extension.

b) All models report an increase of backup energy at the end of the century. This increase is approximately independent of the grid expansion for 3/5 models. For the other two models the increase is even more pronounced for a strongly interconnected grid (large α).

c) The relative change of backup energy features a steeper increase with grid expansion as compared to **b**. Highly connected systems can suffer from an increase of backup needs of up to 7%.

The information taken from the caption is added in lines 180-185, page 10:

... with a factor α. Without any grid, approximately 45 % of the wind-energy is produced at the wrong time and thus has to be curtailed and backed up later on. A strong grid extension ($\alpha \gg 1$) clearly reduces total balancing needs backup energy to about 27% (cf. Fig. 2a). However, all models report an increase of backup energy at the end of the century. The the effect of climate change is almost independent of a grid extension: The absolute increase of backup energy until end of century is largely independent of the expansion coefficient α for three out of five models (cf. Fig. 2b). Hence, the relative increase of backup needs paradoxically becomes even more pronounced for a strongly interconnected Europe (cf. Fig. 2c) Highly connected systems can suffer from an increase of backup needs of up to 7%.. There is considerable...

Caption of Fig. 4, p. 17:

Correlation changes of wind timeseries averaged over all models (difference between end of century and reference correlations). An increase of spatial correlation over most of Europe is found which hints to more homogeneous wind conditions.

This increase is most pronounced in the Central European region. However, at the margins of the continent correlation decreases are found. A more detailed assessment, which in particular addresses inter-model spread, is shown in Fig. 5.

Caption of Fig. 6, p. 21:

Backup energy and change of occurrence as a function of the f-parameter. a) Monotonous decrease of backup energy with increasing f-parameter Backup energy versus f-parameter for the entire domain. Circles denote the mean over the three considered periods for each model and errorbars indicate the standard deviation thereof. **b)** The same decline is found if only Germany plus its neighbor countries are considered. Same as **a)** but restricted to Germany and its neighbors **c)** Change of occurrence of different f-parameters. The change of occurrence is computed as the difference between end of century and the reference period and is given in units of the total number of timesteps N_{tot}. Low f-parameters become more frequent by the end of the century while medium to high f-parameters occur less often. There is considerable inter-model spread, however 16/22 agree on an increase in frequency of very low pressure events ($f < 5$) and 17/22 agree on a decrease of medium pressure events ($10 \leq f < 15$). Red diamonds denote the ensemble mean, red lines the ensemble median and hatched boxes indicate the 33rd to 67th percentile. If a box lies completely above/below zero, the sign of the change can be considered as likely (Mastrandrea et al., 2010).

Caption of Fig. 7, p. 22:

Changes of relative occurrence of primary CWTs with low f-parameters ($f \leq 5hPa/1000km$). Changes are differences in occurrence between end of century and the reference period and are given in units of the total number of timesteps N_{tot}. Boxes indicate the 33rd to 67th percentile and are only shown if changes are substantial. A majority of models projects more weak anticyclones while cyclonic CWTs occur less often (both findings are likely). In total, most models project an overall increase of the occurence of CWTs with low f-parameters. This increase is dominantly rooted in more frequent anticyclonic CWTs. Red diamonds denote the ensemble mean and red lines denote the ensemble median.

Minor Point 2

The abstract tends to over-emphasize the results without actual quantifications, which could be misinterpreted and used against wind energy if taken out of context. For example, rephrase as this: ... we find a robust but modest increase (up to 7%) of backup needs... and ... resulting in parallel generation shortfalls of up to XX MW (corresponding to YY% of power demand) in up to ZZ% of the countries.

Author's response

We thank the reviewer for his/her comment to this very important section of the paper and propose to include his comments as given below.

Changes in the manuscript

> Following a high emission pathway (RCP8.5), we find a robust but modest increase (up to 7%) of backup needs in Europe until the end of the 21st century. The absolute increase of the backup needs is almost independent of potential grid expansion, leading to the paradoxical effect that relative impacts of climate change increase in a highly interconnected European system. The increase is rooted in more homogeneous wind conditions over Europe resulting in extensive parallel intensified simultaneous generation shortfalls. Individual country contributions to European generation shortfall increase by up to 9 TWh/y, reflecting an increase of up to 4%. Our results are strengthened by comparison with a large CMIP5 ensemble using an approach based on Circulation Weather Types.

Minor Point 3

Line 110: please explain how the extrapolation to 80 m was done. Log law? Power law? Interpolation of model levels?

Author's response

When writing the manuscript, we decided to give this information in the supplement in an attempt to keep the manuscript concise. The Supplementary Material, A) Detailed Methodology states:

"Adopting the approach of Tobin et al. (2016), we use near-surface wind speeds 10 meters above the ground. Assuming a power-law relationship for the vertical wind profile, the velocity at hub height H is obtained as

$$v_H = v_{10\mathrm{m}} \cdot \left(\frac{H}{10}\right)^{\frac{1}{7}} \tag{1}$$

and we chose $H = 80\mathrm{m}$."

However, since there are multiple ways to perform the vertical scaling, we agree that it is important to modify the main text such that it includes the words 'power law'.

Changes in the manuscript

See Reviewer 1, Minor Point 4 as this deals with the same sentence.

Minor Point 4

Line 111: which standard power curve was used? How were wake losses accounted for?

Author's response

Similar to the previous point, we thought that the specifics of the calculation are ideally given in the Supplement. The Supplementary Material, A) Detailed Methodology states:

"The conversion of wind speeds into renewable generation is performed using a simple power curve

$$P(v_H) = P_0 \begin{cases} 0, & \text{if } v_H < v_i \text{ or } v_H > v_0 \\ \frac{v_H^3 - v_I^3}{v_R^3 - v_I^3}, & \text{if } v_I \leq v_H < v_R \\ 1, & \text{if } v_R \leq v_H < v_0 \end{cases} \qquad (2)$$

where v_H denotes wind velocity at hub height and $v_I = 3.5$ m/s, $v_R = 12$ m/s, $v_0 = 25$ m/s denote the cut-in, rated and cut-out velocity of the wind turbine, respectively."

Wake losses are not accounted for despite the fact that they reduce wind park yields. We argue that our findings are not severely impacted by this simplification. This is mainly because we focus on changes in wind generation and ignore wake losses both in the reference period and in future periods. While wake losses are likely to change absolute results, it seems plausible that they would impact system operation in the same way under current and future climate conditions. Moreover, it is -to our knowledge- still state-of-the-art either to neglect wake losses (e.g., Andresen et al., 2015) or to apply a bias-correction with measured generation data (e.g., Staffell and Pfenninger, 2016; Gonzalez Aparcio et al., 2016). In addition to wake losses, the bias-correction combines a large number of effects (e.g. unresolved orography, low temporal sampling, local wind phenomena, siting of wind parks, model errors). We are not aware of any reason that this aggregate of effects has to remain constant in time. For a long-term climate change study we thus argue that no bias-correction does less harm than a potentially wrong bias correction. However, it is desirable to develop a process-based representation of wake effects for future research. This would require to combine regional climate models and electricity system models rather than feeding the output of climate models into electricity models.

We agree with the reviewer that (a) information about the power curve should be already given in the methods section and (b) a clear statement that wake losses are neglected should be included.

Changes in the manuscript

> Near-surface wind speeds are scaled up to hub height (80 m) based on a power law and a standard power curve is used to obtain the power generation of the wind turbines, both as in Tobin et al. (2016) (see also Supplementary Material A). The power curve assumes a cut-in velocity of 3.5 m/s, a rated velocity of 12 m/s and a cut-out velocity of 25 m/s. Wake losses are not accounted for. The country-wise aggregated ...

Minor Point 5

Line 113: Why were the wind farms sized at 100 MW?

Author's response

In principle, we follow the partially random allocation approach of Monforti et al. (2016). They argue that "the spatial allocation of future wind turbines (...) is difficult to forecast, as the localization process is dependent on social as well as economic and practical aspects, and are thus generally difficult to investigate." However, they find that "the actual deployment of national wind turbine fleets in 2020 in a country is expected to have a little overall influence on the main features of the national wind power profiles".

The approach necessitates to define the power of a wind park unit. While Monforti et al. (2016) used wind parks of 20 MW, we decided to use 100 MW. The main reason for this choice is that we consider a scenario where 100% of electricity is generated from wind turbines (on average), while Monforti et al. (2016) use the EU 2020 plans that lead to 10% generation from wind turbines. That is, we use five times larger parks to produce ten times the amount of electricity thus leading to more 100 MW wind parks in our assessment than 20 MW wind parks in their assessment. We are hence confident that errors arising from the discretization of wind parks in our assessment are smaller than in Monforti et al. (2016).

Moreover, turbine capacity has increased substantially while wind turbines matured (Wiser et al., 2016) and benefits arise from combining multiple turbines as maintenance and construction costs can be reduced. We hence assume that a future increase in wind park size is plausible.

Changes in the manuscript

> The country-wise aggregated wind power is obtained by summing the generation of 100 MW wind parks until the system is fully-renewable on average. The wind park size was chosen as a compromise between increasing turbine capacities (Wiser et al., 2016) and the need for a sufficient amount of distinct parks. Wind parks are deployed semi-randomly

Minor Point 6

Table 1: this table is not needed and could easily be incorporated either in the main text or in the legend/caption of Figure 2.

Author's response

We agree with the reviewer that the information could be easily incorporated into the text or into a caption. Nevertheless, we prefer to keep the table because it is a lot easier to refer to a table than some section of the text. Note that the table is referenced three times in different sections of the paper.

Minor Point 7

Figure 2: please use the same colors for the 5 models as in Figure 6 and 7 for consistency.

Author's response

We thank the reviewer for pointing us to this shortcoming and adopt Figure 2 accordingly.

Changes in the manuscript

see Reviewer 1, Minor Point 9

Minor Point 8

Figure 2: What are the units of a) and b)? Lref ? Shouldnt it be percent?

Author's response

a) and b) are given in units of the total European load D_{tot}. Unfortunately, the axis label still referred to an older version of the manuscript. Instead of L_{tot} it should read D_{tot} which is defined as

$$D_{\text{tot}} = \int \sum_i D_i(t)dt. \quad (3)$$

Note that the demand is assumed to remain constant such that D_{tot} is the same number for all periods.

We decided not to use percent as unit in a) and b) to facilitate understanding the difference to c). While a) and b) refer to absolute values (expressed as fractions of D_{tot}), c) refers to relative changes of the backup energy (both numerator and denominator depend on $E_B(ref)$).

If a) and b) were to be expressed in percent, the y-values would increase by a factor of 100.

Changes in the manuscript

The unit of the y axis in Fig. 2a,b is now D_{tot} (see Reviewer 1, Minor Point 9). Moreover, the caption gives the definition ($D_{\text{tot}} = \int \sum_i D_i(t)dt$) of the total load (see Reviewer 1, Minor Point 1).

Minor Point 9

Figure 2c: Do you really need this figure? It has the same pattern as b) and it is difficult to conceptualize/understand. Also, having 2 figures instead of 3 would make them more readable. Right now they are too small.

Author's response

Both reviewers comment on this Figure (see Reviewer 2, Minor Point 8). Both propose to remove one panel in order to have more space for the individual subplots. Interestingly, Reviewer 1 suggests to remove c) stating that it has the same pattern as b) while Reviewer 2 suggests removing (or shrinking) a).

We think that the underlying problem is the size of the figure and we agree that it is too small. In terms of removing some content, we argue that all three panels add value and none of them can be easily left out because

a) allows for comparison of results with the literature (e.g., Rodriguez et al., 2014) and shows the potential range of backup energy reduction based on transmission. We suppose that this panel is particularly important for readers without a background in renewable energy integration as it gives an impression of scale and relevance: Roughly 45% of wind generation comes at the wrong time if no inter-country or temporal balancing is allowed.

b) indicates that the absolute increase is largely independent of grid expansion for three models. This is an indication for a large-scale effect and connects this section with the correlation and CWT analysis.

c) highlights that the relative change can be as high as 7 % and is substantially higher under strong grid extension. Given that current strategies of integrating renewables strongly build upon grid expansion, it is an important conclusion for policy making that those system are most vulnerable to climate change.

We thus suggest to keep all three panels but arrange them differently, such that readability is enhanced.

Changes in the manuscript

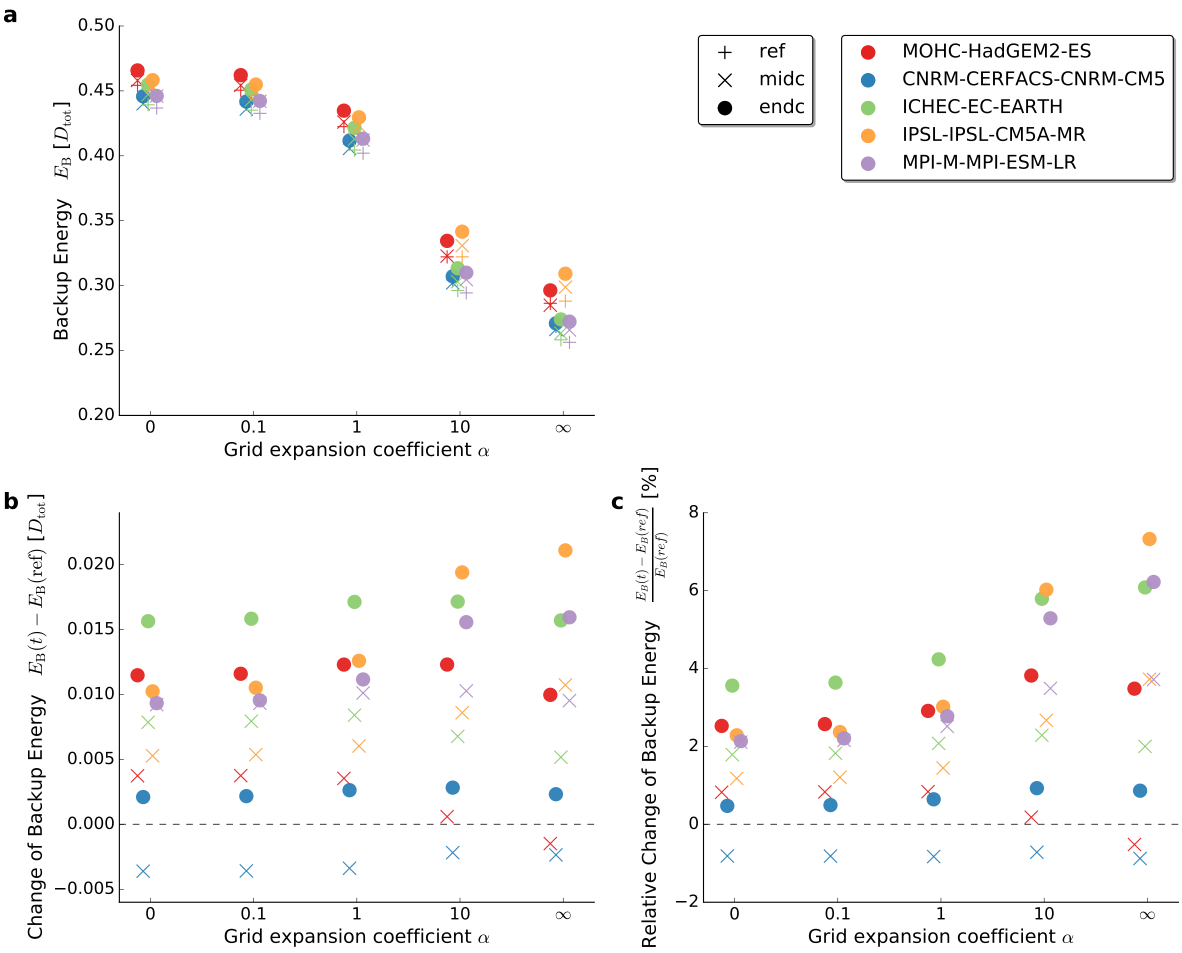

Figure 1: **Updated version of Fig. 2**

Minor Point 10

Line 209: Is L the same as generation shortfall? Please mantion in what units it is expressed (MWh/yr)

Author's response

Yes, the unit of L is $[L] = 1\,\frac{\mathrm{TWh}}{\mathrm{y}}$.

L is not exactly identical to generation shortfall. It is the sum of local generation shortfalls *during European scarcity*. We propose to use both expressions ('energy that is lacking' and 'generation shortfall') because readers may disagree with respect to which one is more intuitive.

Changes in the manuscript

> "We define the annual energy that is lacking (i.e., generation shortfall) in country i during European scarcity ... for convenience of interpretation. L_i is given in TWh/y. A high value of ..."

Minor Point 11

Around line 215: Please compare the values of L with the total energy or capacity of each country. For example, from Figure 3 the maximum size of L is around 250 TWh/yr, which is possibly small for Germany but would be large for Hungary. Maybe a fraction of total electricity consumption should be used instead? Basically, we need a sense of how significant a given value of L is.

Author's response

We thank the reviewer for his/her comment which we have intensively discussed before submission. We think that the reviewer's comment raises the question of perspective. Different questions seem relevant or significant from different points of view. In Fig 3a we decided that we take a European perspective and ask: How much does every individual country contribute to the European problem (i.e. lacking energy L_{ref})? These numbers are biased in the sense that large consumers (such as Germany) have larger contributions than small consumers (like Hungary) due to their size.

One could certainly follow the reviewer's strategy and take a national perspective. What is the fraction of L_{ref} divided by the electricity consumption D_i in each country? However, these numbers are also biased in another sense. If a big country has a small L_{ref} to D_i ratio, it might seem to contribute little to the European problem even if it does contribute substantially.

Since both modes of presentation have their use and give answers to different questions, our idea was to show parts of both approaches. While Fig. 3a takes the European perspective, Fig. 3b takes the national one.

With respect to the units used, we argue that the choice is arbitrary and conventions seem to differ across disciplines. Our colleges dealing with energy system models prefer expressing energies in kWh and we decided to follow their convention.

In any case, we totally agree with the reviewer that the values of L_{ref} should be given for comparison. We thus provide the European aggregate value in the text and add a table to the Supplementaries giving the national values.

Changes in the manuscript

p. 12, line 213:

> ... whereas a low value of L_i indicates a country whose generation shortfall can often be balanced by imports. In order to compare values of L_i with loads, we provide country values for D_i in the Supplementary Material E. The European sum is $\sum_i D_i \approx 3100$ TWh.
>
> Values for ν and L during the reference period are shown in Fig. 3a,b. Large consumers like Germany and France are also the dominant contributors to European scarcity in terms of missing energy (cf. Fig. 3a). The German contribution corresponds to approximately 8% of the European annual load of 3100 TWh. However, the role of these countries, for example, in comparison to Eastern Europe or Benelux, is less pronounced if only the occurrence of negative mismatch events ν is considered...

We add the following table to the supplementaries:

Table 1: Annual sums of country electricity consumption based on hourly 2015 data provided by the European Network of Transmission System Operators for Electricity (2015).

country	**country code**	**Annual load [TWh]**
Austria	AT	69.62
Belgium	BE	85.22
Bulgaria	BG	38.62
Switzerland	CH	62.06
Czech Republic	CZ	63.53
Germany	DE	505.27
Denmark	DK	33.9
Estonia	EE	7.93
Spain	ES	248.5
Finland	FI	82.5
France	FR	471.26
Great Britain	GB	282.19
Greece	GR	51.4
Croatia	HR	17.19
Hungary	HU	40.75
Ireland	IE	26.57
Italy	IT	314.35
Lithuania	LT	10.86
Latvia	LV	7.07
Montenegro	ME	3.42
Macedonia	MK	7.84
Netherlands	NL	113.25
Norway	NO	128.65
Poland	PL	149.96
Portugal	PT	48.93
Romania	RO	52.31
Sweden	SE	135.93
Slovenia	SI	13.65
Slovakia	SK	28.21
Total		3100.94

Minor Point 12

Line 324: please provide a definition/formula of f. Is it the Coriolis parameter?

Author's response

For the determination of the CWTs the sea level pressure at 16 horizontal grid points around a pre-defined central point (in this case near Frankfurt, Germany) is considered (see also Fig. 2 in Reyers et al., 2015). The f-parameter describes the mean horizontal pressure gradient over the domain defined by these 16 grid points and thus can serve as a measure for the wind speed conditions at the central point and the surrounding area.

$$f = \sqrt{dP_z^2 + dP_m^2} \tag{4}$$

where dP_z is the mean pressure gradient in East-West direction (zonal component) and dP_m is the mean pressure gradient in North-South direction (meridional component).

Changes in the manuscript

Aside from the direction of the atmospheric flow a f-parameter is calculated, which is representative for the instantaneous pressure gradient and thus for the general wind speed conditions over Germany and the surrounding countries.:

$$f = \sqrt{dP_z^2 + dP_m^2}, \tag{5}$$

where dP_z is the mean pressure gradient in East-West direction (zonal component) and dP_m is the mean pressure gradient in North-South direction (meridional component). f-parameters from below 5 hPa per 1000 km (weak MSLP gradient and thus low wind speed conditions)

Minor Point 13

Figure 6: cannot see the error bars in a) and b).

Author's response

This is probably because the error bars are most often smaller than the circles. However, they should be clearly visible for CNRM-CM (blue circles) and $f > 20hPa/1000km$. We agree that this is potentially misleading and hence propose to adapt the caption.

Changes in the manuscript

> Circles denote the mean over the three considered periods for each model and errorbars indicate the standard deviation thereof. Errorbars are, however, most often smaller than the circle size.

Spelling Comment 1

line 60: double parenthesis and note that you need a comma after e.g. (e.g., Chiacchio et al. 2015; Herwehe et al. 2014).

Author's response

We correct the quotation accordingly.

Spelling Comment 2

line 92: double parenthesis and note that you need a comma after e.g. (e.g., Bloomfield et al. 2016).

Author's response

Quotation does not exist any more at this place. See Reviewer 2, Minor Comment 3.

Reviewer 2

We thank the reviewer for his or her clear comments and suggestions to improve the manuscript.

Major Point 1/ General Comment

I consider that this manuscript should be subject to minor revision due to the fact that the analysis of the results if often unclear given their definitions and use for expressions such as backup energy and backup needs. Given that the article has been submitted to a journal where authors and readers come from a diverse range of backgrounds, I believe that a clear nomenclature is fundamental. Instances of these conflicts, along with an extended set of minor points is included next, with suggestions on how to improve the manuscript.

Author's response

We fully agree that an interdisciplinary readership requires exact and clear language in order to enable everyone to follow the manuscript. With respect to the example of 'backup energy' and 'backup needs', we used them as synonyms because we thought some variety of language might make the reading more pleasant. However, we agree with the reviewer that this and other parts of the manuscript are confusing, and therefore decided to clarify it in the revised version.

Changes to the manuscript

1. We use the term 'backup energy' throughout the paper and substitute 'backup needs' with 'backup energy' in lines 5, 6, 123, 127, 131, 163, 171, 174, 178, 184, 201, 244, 248, 255, 334, 339, 345, 319, 355, 363,372.

2. We replace 'backup energy needs' by 'backup energies' in lines 150 and 333.

3. We give more details regarding the meaning of a coarse-scale representation of the power system (see Reviewer 2, Minor Point 2)

4. The derivation of the model equations is expanded to make it easier to follow for people without a background in energy related research (see Reviewer 2, Minor Point 9).

Minor Point 1

Page 3, lines 60-61: extra parenthesis in citation

Author's response

We corrected this mistake, see Spelling Comment 1 of Reviewer 1.

Minor Point 2

Page 3, line 32: high resolution future projections but coarse representa- tion of the power system? This might require a better description of the implications and assumptions. Are you considering the effect of changes in the national grids negligible?

Author's response

We assume that the reviewer refers to page 3, line 82.

The meaning of *'coarse scale view on the power system'* is that we neglect many details of real power systems (because they do not matter for the large-scale energy balance of generation and demand). For example, we neglect stability issues (e.g., n-1 criterion, supply of apparent power, cascading effects etc.). The real transmission network is furthermore a system of systems with different voltage levels designed to serve different purposes (transmission over long distances vs. appropriateness for end users) and it is controlled by different actors on multiple levels (e.g. Transmission System Operators and Distribution System Operators). This list is by no means complete and we do not try to capture any of these. Instead, what matters for changes in wind energy (balancing) potentials is a high-resolution representation of wind speeds both in space and time. Therefore we need *'high-resolution regional climate modeling results'*.

With respect to the reviewer's last question: On the contrary, we assume that all national grids have unlimited transmission capacities as explained in p.6 lines 137f. ('We assume all countries to run a loss-free and unlimited transmission network within their boarders.') and in lines 113f. ('The country-wise aggregated wind power is obtained by summing the generation of 100 MW wind parks until the system is fully-renewable on average.') That is, all countries expand their grids such that the maximum benefit from spatial balancing within the country is achieved. The approach is well established as similar representations of the power system have been employed in various earlier studies (Rodriguez et al., 2014, 2015b,a; Becker et al., 2014a,b; Schlachtberger et al., 2017).

Changes in the manuscript

In order to give an idea of assumptions behind our coarse scale approach and facilitate readability for an interdisciplinary audience we propose to add a sentence:

> "In this article we study the impact of climate change on the operation conditions for future fully-renewable power systems. We combine the analysis and simulation of power systems with high-resolution regional climate modeling results to quantify changes in wind power generation. We adopt a coarse scale view on the power system to uncover the large-scale impacts of climate change. The coarse scale perspective neglects details that are irrelevant for the balancing of demand with wind generation such as supply of apparent power or different voltage levels in the grid. The focus of this study is to In particular, we address the potential of trans-national power transmission to cover regional balancing needs."

Minor Point 3

Page 5, lines 92-94: This paragraph looks out of place in the Methods section and is redundant to the Introduction

Author's response

We agree with the reviewer and delete the paragraph. The citation is added in the Introductory as the paper contributed substantially to the research field.

Changes in the manuscript

Page 5, lines 92-94

> The power generated by wind turbines and solar photovoltaics is determined by the weather such that its variability crucially depends on atmospheric conditions (see, e.g. Bloomfield et al. (2016)). How does climate change affect these conditions and the challenges of system integration?

Page 3, lines 73-74

> It is thus necessary to consider indicators such as the variability and synchronicity of generation in addition to total energy yields (Monforti et al., 2016; Bruckner et al., 2014; Bloomfield et al., 2016).

Minor Point 4

Page 5, line 102: should be sensitivity analyses or a sensitivity analysis

Changes in the manuscript

In the spirit of a sensitivity analyses analysis, we evaluate the representative concentration pathway RCP8.5.

Minor Point 5

Page 6, eqs 1-2: You dont include any representation of existing storage capacity in the system? How would results change if you did?

Author's response

Yes, we neglect storage in this paper. This is done on purpose following a separation approach. The issue of variable renewable generation can in principle be solved via (a) spatial balancing or (b) temporal balancing or any combination of them. The paper under review here follows strategy (a) while another paper from our group follows strategy (b) (Weber et al., 2017). We plan to combine both approaches in future work. However, in order to understand the coupled system, it is helpful to have understood the isolated systems first.

One main challenge in combining both strategies is to incorporate the decision making process. Assume a country which has sufficient renewable generation at a certain point in time to meet its own demand completely while its storage is half full. Would it aim to import electricity to further fill its storage? Or would it rather sell the energy it has stored? Or would it prefer not to do anything? This decision would also very likely depend on the forecasted generation for the next days. If lots of wind generation for the days ahead is predicted, the country would be more likely to sell its stored electricity. In restricting our analysis to one option at a time, these problems are muted for the moment. However, they do have to be tackled in future works.

Inclusion of the *current* storage capacities would have a small effect on backup energies. For example, the current German storage capacity is around $S = 0.04$ TWh (Weitemeyer et al., 2015) while the German annual electricity consumption is at the order of $D_{\mathrm{Ger}} = 500$ TWh. The fraction $S/D_{\mathrm{Ger}} = 8 \cdot 10^{-5}$ is hence small and allows to store a bit less than 45 minutes of average German load. Weitemeyer et al. (2015) study the effect of storage on a renewable German power system with a mix of PV and wind for different renewable penetrations. They find that a storage of 0.1 TWh would allow to reduce backup energy by around 5% as compared to a no storage scenario in a fully-renewable system (see Fig. 2 in Weitemeyer et al., 2015). The effect of *current* storage capacity on the system studied in our paper is considerably smaller because (a) the current storage size is only 40% of 0.1 TWh and (b) they incorporate 40% PV generation which can be more easily stored than wind because it dominantly follows a diurnal cycle. Potential backup energy reductions due to current storage are thus at the order of 1%. This is clearly smaller than the potential reductions from grid expansion studied here (roughly 15% for $\alpha = 10$, see Fig. 2a).

However, including *very large* storage infrastructure would even have the ability to reduce backup energies to zero in the simplified system studied here (if energy losses from conversion are neglected). This is due to to the long-term balance between generation and load (Supplementary, Eq. 4). Unlimited storage would shift excess energy from periods of overgeneration to periods when generation shortfall is experienced.

Minor Point 6

Page 6, line 151: a 20yr time slice only allows to account for a portion of natural variability: interannual rather than decadal, and you mention in your introduction that larger time-scales also have an impact on the power system operation

Author's response

We do agree that the sentence overstates and needs to be relativized since we certainly ignore variability on very long timescales. We also agree with the reviewer that a 20 year time slice does not allow to assess decadal variability in a meaningful way. However, we do not consider one 20 year time slice but five of them because we use the output of five different models. Since the models have no reason to be synchronized, it is plausible to assume that they are in different states with respect to modes of natural variability. A *robust* change across all models (such as the increase in backup energy reported in the paper) is hence likely not rooted in decadal variability with a recurrence time of a couple of decades.

Changes in the manuscript

We suggest to replace the sentence by the (slightly modified) more accurate explanation in the table caption

> Time frames of 20 year duration are chosen to account for natural climatic variability (see Table 1).
>
> Time frames are chosen to contain 20 years in order to capture natural variability of the climate system on a multi-year timescale while still ensuring that elapsed time between periods is long enough to consider them distinctly (see Table 1). Since GCMs do not reproduce natural variations synchronously (Farneti, 2017), robust signals found in the ensemble are very unlikely to be rooted in natural variations with a recurrence time of a couple of decades (such as the Atlantic Meridional Oscillation or the North Atlantic Oscillation; see Peings and Magnusdottir (2014) for a discussion of their role in mediating atmospheric conditions).

The new caption of table 1 then reads:

> Periods are chosen to contain 20 years in order to capture natural variability of the climate system on a multi-year timescale while still ensuring that elapsed time between periods is long enough to consider them distinctly. Since GCMs do not reproduce natural variations synchronously (Farneti, 2017), robust signals found in the ensemble are very unlikely to be rooted in natural variations with a recurrence time of a couple of decades (such as the Atlantic Meridional Oscillation or the North Atlantic Oscillation; see Peings and Magnusdottir (2014) for a discussion of their role in mediating atmospheric conditions). The reference period ref ends before 2005 because GCMs in CMIP5 are driven by historic emissions only until this date and follow different representative concentration scenarios afterwards.
>
> Periods used in this study. The reference period ref ends before 2005 because GCMs in CMIP5 are driven by historic emissions only until this date and follow different representative concentration scenarios afterwards.

Minor Point 7

Figure 1 and Table 1 captions: These are very long. Consider including more of this information (which even includes multiple references!) in the Methods section.

Author's response

We thank the reviewer for making us aware of this shortcoming.

Changes in the manuscript

We provide a common answer in Reviewer 1, Minor Point 1 as both critiques are identical.

Minor Point 8

Figure 2: one really cant tell much from panel a on this figure. Consider removing it and using only the changes, or just show it for fewer expansion coefficients (or just no expansion) to be able to zoom in. On the caption, there is a typo and should read later on. And you are also discussing a lot of the results on the caption!

Author's response

We thank the reviewer for his feedback on this Figure and agree largely.

Changes in the manuscript

The general criticism is similar to Reviewer 1, Minor Point 9 where we provide a common answer.

Moreover, we correct the typo and shorten the captions as given in Reviewer 1, Minor Point 1.

Minor Point 9

Page 10, lines 75-77: The assessment is not clear. An increase in backup energy needs implies under your definition that there is more of the local energy mismatch (difference between demand and volatile RE) that could not be met by transmissions. So, how can this be due to more excess energy? Is the problem on the assessment of line 74, since the increase is not on backup NEEDS but rather on energy available for transmission? If what you show on the plot (panel a) is back up energy, that is decreasing with network expansion. You can see how your descriptions are leaving big gaps in the interpretation of results.

Author's response

We suppose that there is a misunderstanding here which can easily be resolved. In the system under consideration, more backup energy directly leads to more excess energy and excess energy has to be curtailed. This is because we assume that renewables generate as much electricity as needed on average. The statement can be formally derived from Eq. (2) in the manuscript by summing over all countries i and integrating over an entire period from t_s to t_e which yields:

$$\int_{t_s}^{t_e} \sum_i M_i(t)dt + \int_{t_s}^{t_e} \sum_i B_i(t)dt + \int_{t_s}^{t_e} \sum_i F_i(t)dt = \int_{t_s}^{t_e} \sum_i C_i(t)dt. \tag{6}$$

Recall that M_i is the mismatch, B_i is backup power, F_i denotes imports or exports and C_i denotes curtailment. The first term in Eq. 6 vanishes because of the assumption of a fully-renewable system (cf. Supplementary Eq. 12). The third term also vanishes because every import in one country ($F_j > 0$) is an export in another ($F_k < 0$) such that in total all imports are balanced by exports ($\sum_i F_i(t) = 0$). It follows that

$$\int_{t_s}^{t_e} \sum_i B_i(t)dt = \int_{t_s}^{t_e} \sum_i C_i(t). \tag{7}$$

The left hand side is the backup energy E_B as defined in Eq. (3) in the manuscript and the right hand side is European curtailment during a period. (Note that Eq. 3 in the manuscript includes a minimization of B_i which is needed to determine the im- and exports. For an aggregated European assessment, the actual im- and exports do not matter since they cancel anyway as argued above.)

Changes in the manuscript

We suggest restructuring of the sentence as follows

> The increase implies more excess energy and also more curtailment since we consider a scenario where 100% of electricity is generated from renewables on average.
>
> Since we consider a scenario where 100% of electricity is generated from renewables on average, an increase of backup energy is accompanied by an increase of excess energy which has to be curtailed.

Moreover, we add some information to the methods section to enhance readability for non-experts in the field of energy research:

p. 6, lines 137-138: The assumption of a fully-renewable system means that all countries generate as much electricity as needed on average ($\int_{t_s}^{t_e} M_i(t)dt = 0$). Furthermore, we We assume all countries to run a loss-free and unlimited transmission network within their boarders.

p. 6, lines 139-147:

If a country has a negative mismatch ($M_i < 0$, red circles in Fig. 1d), it tries to import energy. If it has a positive mismatch ($M_i > 0$, green circles in Fig. 1d), it tries to export energy. For each country i the power balance must be satisfied:

$$M_i(t) + B_i(t) + F_i(t) = C_i(t),. \tag{8}$$

The mismatch M_i can be compensated either by power generation from conventional backup power plants ($B_i \geq 0$), the curtailment of renewable power generation ($C_i \geq 0$) or by imports ($F_i > 0$) or exports ($F_i < 0$). To utilize renewable generation in an optimal way, countries will first try to balance power using im- and exports. However, a perfect balancing of all nodes is impossible if there is a continent-wise shortage or overproduction. Furthermore, cross-boarder flows along lines are bound by the directional Net Transfer Capacities (NTCs; see Supplement A for details), which may also impede balancing for some nodes. Power balance must then be satisfied by local means: In the case of a shortage, power must be backed up by conventional generators ($B_i > 0$). where F_i represents imports ($F_i > 0$) or exports ($F_i < 0$) to/from country i. Cross-boarder flows along lines are bound by the directional Net Transfer Capacities (NTCs; see Supplement A for details). If overall shortage or line limits prohibit sufficient imports, power can also be backed up locally ($B_i \geq 0$). Similarly, if excess power can not be exported, it has to be curtailed ($C_i \geq 0$). We recognize that the technical details of backup generation often matter for implementation (Schlachtberger et al., 2016) but we focus on gross electricity needs in this study.

Additionally we add on page 7, line 155:

The European amount of backup energy is identical to the amount of curtailment over a full period. This is a direct consequence of the assumptions made and can be formally derived by summing Eq. 6 over all countries and integrating over an entire period. Since $\int_{t_s}^{t_e} M_i(t)dt = 0$ (each country is fully renewable on average) and $\sum_i F_i = 0$ (all imports to one country $F_j = c$ are exports from another $F_k = -c$) it follows that:

$$\int_{t_s}^{t_e} \sum_i B_i(t)dt = \int_{t_s}^{t_e} \sum_i C_i(t). \tag{9}$$

A change of the backup energy thus directly implies a change in total curtailment.

Minor Point 10

Page 10, lines 183-184: this is not true for all ensemble members. Cahnges in CNRM and MOHC are not that pronounced.

Author's response

While there is also an increase for CNRM and MOHC, we agree that the sentence is not strictly true for the two models mentioned. Given that the subsequent sentence deals with the considerable inter-model spread we suppose to add another sentence after this one.

Changes in the manuscript

> There is considerable inter-model spread regarding the magnitude of change which varies by up to one order of magnitude depending on the climate model (see Fig. 2b, $\alpha = \infty$). In particular, changes for CNRM are generally weak and HadGEM2 features only a slight overall increase with grid expansion.

Minor Point 11

Figure 8b, Supplementary Information: How can the backup energy increase by incorporating PV? You can see it in the two larger α values for the CNRM model in the *midc* period.

Author's response

If we understand correctly, the reviewer compares Fig. 2b in the manuscript and Fig. 8b in the supplement. While Fig. 2b always gives clearly negative absolute changes of the backup energy for CNRM, the change of backup energy approaches zero under $\alpha \in [10, \infty]$ in Fig. 8b. This means that the backup energy almost stays constant from *ref* to *midc* if PV is included, while it is reduced when PV is ignored.

To start with, backup energy (in absolute terms) is not higher but lower if PV is included as Figs. 2a and 8a show. For example, for $\alpha = 10$ the backup energy without PV is roughly $E_{\mathrm{B}} = 0.3L_{\mathrm{tot}}$ while it comes down to roughly $E_{\mathrm{B}} = 0.25L_{\mathrm{tot}}$ if PV is included. This decline is to be expected because wind and solar are to some extent complementary and their combination allows to reduce generation shortfall.

The observation that the backup energy decreases for small values of α in Fig. 8b indicates that the climatic changes are beneficial for the isolated or weakly connected European System following CNRM by midc. Grid expansion allows for spatial smoothing of the generation and brings backup energies down (cf. Fig. 8a). However, in a strongly connected system, no further positive effects due to climate change occur.

As a general note, PV is not considered additionally to wind generation in this study but rather as a *substitute* for a certain fraction of wind generation (cf. Supplementary ll. 607 ff.). In those scenarios where PV is included, only 71% of the load has to be met by wind (leading to fewer wind parks) while the remainder is provided by PV.

Minor Point 12

Page 10, line 194: should be reveal

Changes in the manuscript

> Results are barely sensitive to changes in the load timeseries as an assessment using constant loads reveils reveals (cf. Supplementary C).

Minor Point 13

Page 11, lines 199-201: how is this a lower bound to back up needs if this is this represents the worst case scenario for mismatch. I can see how it is a lower bound for the mismatch Mi , since it is negative.

Author's response

We know that backup energy decreases monotonously with grid expansion (see Fig. 2a). This is because a well developed grid allows for spatial integration of volatile renewable generation. The case of unlimited transmission (i.e. $\alpha = \infty$) hence yields the lowest backup energies and provides a lower bound for backup energies. In other words, backup energies in a real system ($\alpha < \infty$) must be higher than the ones discussed in this section.

Minor Point 14

Page 12, line 232: should be importing

Author's response

The argument works in both directions. If a set of countries suffers from generation shortfall while Europe suffers from a generation shortfall, they can neither export electricity to alleviate the *overall* shortage nor import electricity to alleviate *their own* shortage. We prefer to keep the sentence as it is because we want to highlight that these countries can not contribute to solve the overall problem.

Minor Point 15

Page 13, lines 257-259: this clarification should have been made in the Methods section, since it was also an assumption of the previous analysis.

Author's response

We thank the reviewer and agree that the sentence fits better to the methods section.

Changes in the manuscript

We propose to include the sentence in the Methods section, p. 5, ll. 115

> ... following the approach of (Monforti et al., 2016). In order to single out climate change induced alterations, we fix the technological parameters such as hub heights or turbine efficiencies, and we do not account for changes in the consumption such as load shifting or sector coupling throughout the 21st century.

Minor Point 16

Figure 7: check language of labels in x axis. To mix the directions and rotations in the same plot makes it impossible to see any changes in the first. Consider adding two panels!

Author's response

We thank the reviewer for making us aware of the language issues and correct them accordingly.

We would like to stress that we consider 10 distinct CWTs. 8 of them are directional (N, NE, E etc.) and 2 of them are rotational (Anticyclonic, Cyclonic). There are no mixed CWTs in this assessment. The misunderstanding might originate from p.19 lines 321-324 where 'and/or' should read 'or'. We correct this mistake.

Based on this, it is interesting that most of the change is caused by rotational CWTs which is clearly visible in the plot as it is. If we were to use two different panels for directional and rotational CWTs, this information would potentially be masked. We therefore prefer not to add two panels.

Changes in the manuscript

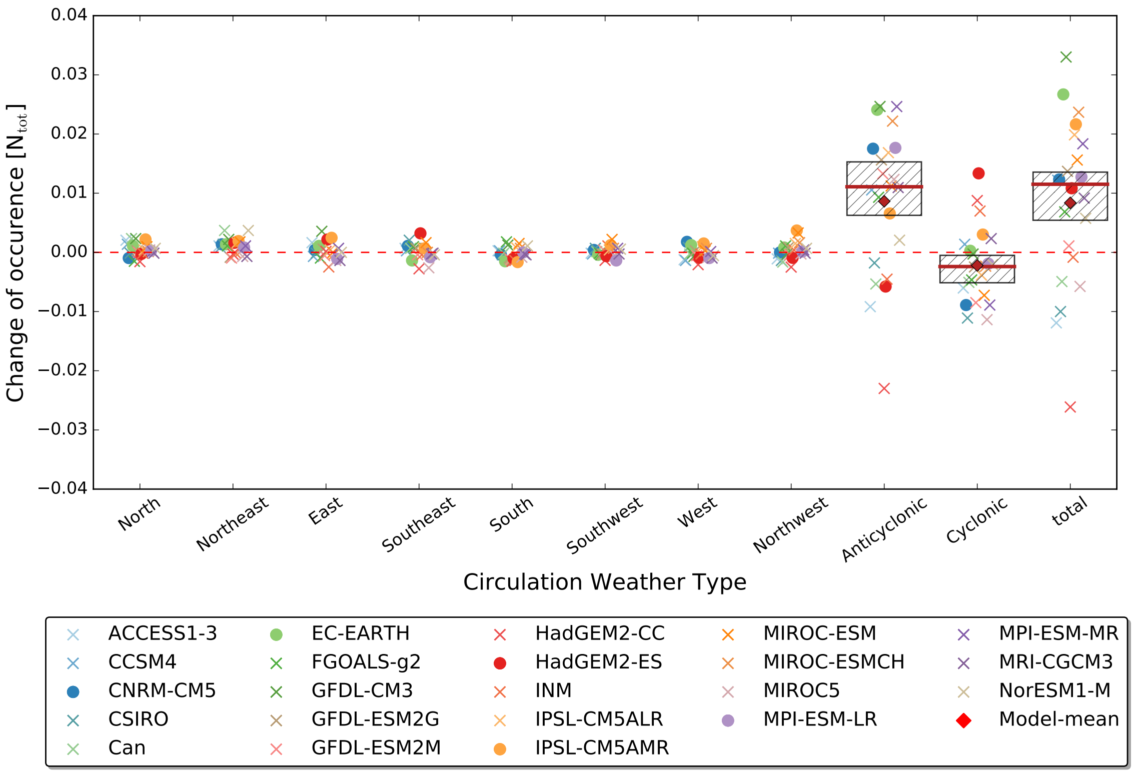

Figure 2: **Updated version of Fig. 7.**

p.19 lines 321-324:

> Daily mean sea level pressure (MSLP) values at 16 GCM grid points around a central point located in Germany are used to assign the near-surface atmospheric flow over Europe to either a directional flow (north, northeast, east, . . .) and/or a rotational flow (anticyclonic, cyclonic).

Minor Point 17

Page 20, lines 345-6: It seems like you are making assumptions about more spatially homogeneous condition from an analysis that is based on a single point. How can you draw those conclusions from CWT?

Author's response

As already stated in the submitted manuscript, for the determination of the CWTs the sea level pressure at 16 horizontal grid points around a pre-defined central point (in this case near Frankfurt, Germany) is considered (see also Fig. 2 in Reyers et al., 2015). Hence, the analysis is not based on a single point but on a horizontal pressure field covering large parts of the European sector. As a consequence, Reyers et al. (2015) could demonstrate that CWTs enable reliable conclusions about the regional wind conditions for a domain which covers Germany and the surrounding countries. It is thus possible to make assumptions about the spatial homogeneity, as stated in the submitted manuscript.

Minor Point 18

Page 23, lines 372-2: Comment starting in Moreover... need revision

Author's comment

We thank the reviewer for his comment and modify as given below. In particular, we correct the percentage from 8% to 7% which is more exact (see Fig. 2c) and in line with the number given in the abstract (see Reviewer 1, Minor Point 2).

Changes in the manuscript

> Moreover, While the increases of backup energy are robust yet , they are also restricted to relative increases of 87% (cf. Fig. 2). A fully-renewable electricity system will hence not become unfeasible due to catastrophic changes.

Other modifications

Update bibliography

The paper (Schlachtberger et al., 2016) has been accepted in the meantime and is now referenced correctly.

Substantial new work by Grams et al. (2017)

Grams et al. (2017) showed that volatility of wind generation can be drastically reduced if wind park locations are chosen based on weather patterns rather than concentrated in the North Sea. We want to include the reference on page 13 line 242 as

> Moreover, Greece shows favourable changes for the European system in terms of energy contributions and occurrences with a high inter-model agreement (cf. Fig. 3c,d). This finding is particularly interesting as Grams et al. (2017) show that a combination of wind parks allocated in the North Sea and the Balkans allows to reduce volatility substantially under current climatic conditions. Based on our results, this positive effect from incorporating the Balkans would further be enhanced under strong climate change.

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Date: 31 August 2017

More Homogeneous Wind Conditions Under Strong Climate Change Decrease the Potential for Inter-State Balancing of Electricity in Europe

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Abstract. Limiting anthropogenic climate change requires the fast decarbonisation of the electricity system. Renewable electricity generation is determined by the weather and is hence subject to climate change. We simulate the operation of a coarse-scale fully-renewable European electricity system based on downscaled high resolution climate data from EURO-CORDEX. Following a high emission pathway (RCP8.5), we find a robust but modest increase (up to 7%) of backup needs energy in Europe until the end of the 21st century. The absolute increase of the backup needs energy is almost independent of potential grid expansion, leading to the paradoxical effect that relative impacts of climate change increase in a highly interconnected European system. The increase is rooted in more homogeneous wind conditions over Europe resulting in extensive parallel intensified simultaneous generation shortfalls. Individual country contributions to European generation shortfall increase by up to 9 TWh/y, reflecting an increase of up to 4%. Our results are strengthened by comparison with a large CMIP5 ensemble using an approach based on Circulation Weather Types.

1 Introduction

Massive reductions of greenhouse gas emissions are needed in order to reach the temperature goals defined in the Paris Agreement (UNFCCC, 2015; Schleussner et al., 2016b). With a share of around 35% of current emissions being caused by the electricity system (Bruckner et al., 2014), its decarbonisation is the key to any mitigation strategy. However, today's pledges are not yet sufficient to limit warming to below 2°C, not to mention 1.5°C (Rogelj et al., 2016).

In addition to the need of mitigating carbon emissions, a second interaction between the energy system and the climate system exists and becomes increasingly important with higher penetrations of renewable energies. Volatile renewable energy generation is driven by weather conditions which are subject to climate change. Large backup facilities are needed to guarantee a stable supply of electricity during periods of low wind and solar power generation (Rodriguez et al., 2014). Furthermore, climate change affects the demand for electric power (Auffhammer et al., 2017) as well as the operation conditions for thermo- and hydroelectric power plants which serve as backup (van Vliet et al., 2016, 2012). However, feedback effects of large-scale wind fleets on atmospheric flows are limited (Vautard et al., 2014).

In line with the Paris Agreement, the scientific community is increasingly interested in differentiating climate impacts at 1.5°C and 2°C (Schleussner et al., 2016a; James et al., 2017) and the IPCC currently prepares a special report on 1.5°C. However, many low-carbon pathways rely on negative emissions during the second half of this century (Rogelj et al., 2015; van Vuuren et al., 2016), although their feasibility at scale remains debated (Anderson and Peters, 2016). Future emissions from existing CO_2-emitting infrastructure (Davis et al., 2010) and current political developments in the US (Trump, 2017), among others, might impede fast decarbonisation. Different climatic futures are hence plausible and mitigation strategies need to work in all of them. Therefore, we are led to the question: How sensitive is a fully-renewable electric power system to climate change? In particular: How severely could strong climate change impact such a system?

Anthropogenic climate change affects the large-scale atmospheric flow and thus the operation conditions for renewable power generation. State-of-the-art global climate models reveal that changes in zonal wind depend on the temperature structure of the lower atmosphere (Haarsma et al., 2013) and that zonal-mean zonal wind and eddy kinetic energy decline almost linearly in time due to polar amplification (Coumou et al., 2015). There are also natural sources of variability on up to decadal timescales. Some of them originate from ocean-atmosphere interactions in the Atlantic and are potentially predictable (Haekkinen et al., 2011; Peings and Magnusdottir, 2014). The North Atlantic Oscillation has been shown to directly influence the operation of inter-connected renewable electricity systems (Ely et al., 2013). Predictability of such natural variations is of great interest for system integration and efforts are undertaken to assess and improve forecasting skills (Moemken et al., 2016).

To assess the impact of climate change on the operation of renewable power systems, downscaled climate model output is needed. It comes at a high temporal and spatial resolution and is better suited than global model output to capture local features such as land-sea transitions or mountains (Rummukainen, 2016). Temporal resolutions at the sub-daily scale are needed since electricity consumption varies strongly during the day. Changes in wind energy yields and capacity factors have been assessed based on dynamical (Tobin et al., 2015, 2016) and statistical-dynamical downscaling outputs (Reyers et al., 2015, 2016). Tobin et al. (2016) evaluate the EURO-CORDEX data archive and find that changes in the annual wind energy yield across Europe are at the order of 5% and models do not agree on the sign of change. Following a different approach that allows for the inclusion of the output of 22 global climate models, Reyers et al. (2016) report an increasing intra-annual gradient between winter and summer wind generation and different trends in Northern and Central Europe as compared to Southern Europe.

Assessing changes in solar power generation is arguably more difficult due to, among others, unresolved processes in relatively coarse climate models and uncertain parameterizations (e.g. (Chiacchio et al., 2015; Herwehe et al., 2014)) (e.g., Chiacchio et al., 2015; Herwehe et al., 2014). Acknowledging this difficulty and associated uncertainties, an evaluation of the EURO-CORDEX data finds limited impacts of climate change on solar photovoltaics (PV) potentials (Jerez et al., 2015). Southern Europe, having the highest potential for PV, sees only small changes, as an increase in downwelling irradiation is counteracted by a decreasing efficiency due to warming. In contrast, the output of concentrating solar power systems (CSP) is expected to increase by around 10% because the efficiency of CSP increases with temperature (Crook et al., 2011).

While wind and solar power sources have shown a remarkable development in the last decades, system integration remains a huge challenge (Huber et al., 2014). In a highly renewable power system the timing of generation events becomes crucial for the system. Even in an European electricity system that is on average fed by 100% renewables, roughly one quarter of the energy is produced at the wrong time and has to be curtailed (Rodriguez et al., 2014, 2015a).

It is thus necessary to consider indicators such as the variability and synchronicity of generation in addition to total energy yields (Monforti et al., 2016; Bruckner et al., 2014; Bloomfield et al., 2016). Several validated timeseries of renewable generation based on reanalysis data are available to assess the power system operation (Pfenninger and Staffell, 2016; Staffell and Pfenninger, 2016; Gonzalez Aparcio et al., 2016). However, these data sets are restricted to current climatic conditions and might thus be misleading for long-term planning of the electricity system.

In this article we study the impact of climate change on the operation conditions for future fully-renewable power systems. We combine the analysis and simulation of power systems with high-resolution regional climate modeling results to quantify changes in wind power generation. We adopt a coarse scale view on the power system to uncover the large-scale impacts of climate change. The coarse scale perspective neglects details that are irrelevant for the balancing of demand with wind generation such as supply of apparent power or different voltage levels in the grid. The focus of this study is to In particular, we address the potential of trans-national power transmission to cover regional balancing needs.

Our results reveal the sensitivity of fully-renewable power systems to climate change. They should not be mistaken with a forecast and rather be considered a thought experiment to assess potential risks and to answer the question: What happens to a fully-renewable electricity system if mitigation actions are ineffective or come too late?

2 Methods

Modeling the operation of a fully-renewable power system under climate change

The power generated by wind turbines and solar photovoltaics is determined by the weather such that its variability crucially depends on atmospheric conditions (see, e.g. Bloomfield et al. (2016)). How does climate change affect these conditions and the challenges of system integration?

To assess the impact of strong climate change, we simulate the operation of a fully-renewable power system making use of high resolution climate projections. We use the EURO-CORDEX ensemble containing output of Global Circulation Models (GCMs) which has been dynamically downscaled to a finer resolution (Jacob et al., 2014) to quantify changes in wind power generation. The ensemble contains five GCMs (HadGEM2-ES, CNRM-CM5, EC-EARTH, CM5A-MR amd MPI-ESM-LR) which are all downscaled by the regional climate model RCA4 (Strandberg et al., 2015). The GCM output is part of the Climate Model Intercomparison Project Phase 5 (CMIP5) and publicly available (Taylor et al., 2011). We use near-surface wind speeds at 0.11° spatial and 3 h temporal resolution and hence capture intra-day effects. In the spirit of a sensitivity analyses analysis, we evaluate the representative concentration pathway RCP8.5. It describes atmospheric greenhouse gas concentrations following a business-as-usual strategy and leads to approximately 4.3°C warming at the end of the century as compared to pre-industrial values (Stocker et al., 2013). In view of inter-model spread and other uncertainties, a strong climate change scenario bears the advantage of high signal-to-noise ratios.

The approach used in this study is illustrated in Fig. 1. The climate data is used to calculate the aggregated wind power generation time series for each country in the interconnected European power grid (grey circles in Fig. 1a). Near-surface wind speeds are scaled up to hub height (80 m) based on a power law and a standard power curve is used to obtain the power generation of the wind turbines, both as in Tobin et al. (2016) (see also Supplementary Material A). The power curve assumes a cut-in velocity of $3.5 \mathrm{~m/s}$, a rated velocity of $12 \mathrm{~m/s}$ and a cut-out velocity of $25 \mathrm{~m/s}$. Wake losses are not accounted for. The country-wise aggregated wind power is obtained by summing the generation of 100 MW wind parks until the system is fully-renewable on average. The wind park size was chosen as a compromise between increasing turbine capacities (Wiser et al., 2016) and the need for a sufficient amount of distinct parks. Wind parks are deployed semi-randomly following the approach of Monforti et al. (2016). In order to single out climate change induced alterations, we fix the technological parameters such as hub heights or turbine efficiencies, and we do not account for changes in the consumption such as load shifting or sector coupling throughout the 21st century. Tests including validated historical PV timeseries (Pfenninger and Staffell, 2016) reveal that the inclusion of PV does not change the overall results (see Supplement B). For the sake of simplicity, we thus decide to restrict the analysis to wind-driven power systems in this paper.

Wind power generation is strongly fluctuating on various time scales as shown in Fig. 1c. In periods of scarcity, energy has to be imported from other countries or generated from local dispatchable power plants. We refer to the latter as backup energy. In the situation depicted in Fig. 1a, scarcity in Southern Europe can mainly be compensated by imports from Northern Europe. Trans-national balancing of this kind often requires large transmission capacities. Moreover, the import of electric energy requires a respective exporter which has a surplus at the same time. Backup needs energy in future renewable power systems are is thus essentially determined by the temporal and spatial heterogeneity of wind and solar power throughout the system.

In addition to enhanced spatial balancing via im- and exports, an extension of storage facilities will reduce backup needs energy (Rasmussen et al., 2012). But storage assets are more costly than grid expansion (Schlachtberger et al., 2017; Brown et al., 2016). Since a cost-optimal solution will thus favor grid expansion, we focus on spatial effects and trans-national balancing. An assessment of climate change effects on storage following a similar approach is presented by Weber et al. (2017).

To quantify backup needs energy, we adopt a coarse-scale view of the transmission system (see, e.g. Rodriguez et al. (2015a, 2014)). We consider each country i to be a node in the European transmission network and define a nodal mismatch for each point in time $t = 1, 2, \ldots$ as

$$M_i(t) = P_i(t) - D_i(t), \tag{1}$$

where $P_i(t)$ is intermittent renewable generation and $D_i(t)$ is the load (here: hourly data for 2015 from European Network of Transmission System Operators for Electricity (ENTSO-E) averaged over 3h timesteps (European Network of Transmission System Operators for Electricity, 2015)). The assumption of a fully-renewable system means that all countries generate as much electricity as needed on average ($\int_{t_s}^{t_e} M_i(t)dt = 0$). Furthermore, we We assume all countries to run a loss-free and unlimited transmission network within their boarders.

If a country has a negative mismatch ($M_i < 0$, red circles in Fig. 1d), it tries to import energy. If it has a positive mismatch ($M_i > 0$, green circles in Fig. 1d), it tries to export energy. For each country i the power balance must be satisfied:

$$M_i(t) + B_i(t) + F_i(t) = C_i(t), \tag{2}$$

The mismatch M_i can be compensated either by power generation from conventional backup power plants ($B_i \geq 0$), the curtailment of renewable power generation ($C_i \geq 0$) or by imports ($F_i > 0$) or exports ($F_i < 0$). To utilize renewable generation in an optimal way, countries will first try to balance power using im- and exports. However, a perfect balancing of all nodes is impossible if there is a continent-wise shortage or overproduction. Furthermore, cross-boarder flows along lines are bound by the directional Net Transfer Capacities (NTCs; see Supplement A for details), which may also impede balancing for some nodes. Power balance must then be satisfied by local means: In the case of a shortage, power must be backed up by conventional generators ($B_i > 0$). where F_i represents imports ($F_i > 0$) or exports ($F_i < 0$) to/from country i. Cross-boarder flows along lines are bound by the directional Net Transfer Capacities (NTCs; see Supplement A for details). If overall shortage or line limits prohibit sufficient imports, power can also be backed up locally ($B_i \geq 0$). Similarly, if excess power can not be exported, it has to be curtailed ($C_i \geq 0$). We recognize that the technical details of backup generation often matter for implementation (Schlachtberger et al., 2016) but we focus on gross electricity needs in this study.

For each time step we determine the system operation which minimizes backup power and thus macroeconomic costs as well as greenhouse gas emissions. To assess the impact of climate change, we compare future backup energy needs to historical values. Time frames of 20 year duration are chosen to account for natural climatic variability (see Table 1). Time frames are chosen to contain 20 years in order to capture natural variability of the climate system on a multi-year timescale while still ensuring that elapsed time between periods is long enough to consider them distinctly (see Table 1). Since GCMs do not reproduce natural variations synchronously (Farneti, 2017), robust signals found in the ensemble are very unlikely to be rooted in natural variations with a recurrence time of a couple of decades (such as the Atlantic Meridional Oscillation or the North Atlantic Oscillation; see Peings and Magnusdottir (2014) for a discussion of their role in mediating atmospheric conditions). The backup energy E_B per period is defined as the sum over all backup powers in a given period:

$$E_\mathrm{B}(\text{period}) = \sum_{t\,\in\,\text{period}} \min \sum_i B_i(t), \tag{3}$$

such that Eq. (2) is satisfied for all countries i and the line limits are respected.

The European amount of backup energy is identical to the amount of curtailment over a full period. This is a direct consequence of the assumptions made and can be formally derived by summing Eq. 2 over all countries and integrating over an entire period. Since $\int_{t_s}^{t_e} M_i(t)dt = 0$ (each country is fully renewable on average) and $\sum_i F_i = 0$ (all imports to one country $F_j = c$ are exports from another $F_k = -c$) it follows that:

$$\int_{t_s}^{t_e} \sum_i B_i(t)dt = \int_{t_s}^{t_e} \sum_i C_i(t). \tag{4}$$

A change of the backup energy thus directly implies a change in total curtailment.

We use climate model ensembles to account for model uncertainties. Interpretating the ensemble output by means of the ensemble-mean can be misleading as a single model might dominate the ensemble. In such cases, the model-mean would be in disarray with the majority of models and hence would not be representative for the ensemble. We thus assess the robustness of changes by means of inter-model agreement. We label a signal *robust* if all models agree on the sign of change and use *high agreement* if all but one model agree. In the evaluation of the large CMIP5 ensemble we adopt language defined for the latest IPCC report and label a change *likely* if at least 66% of models agree (Mastrandrea et al., 2010).

A variety of studies have analyzed transmission and backup needs energy in future renewable power systems and cost-optimal transition pathways in a similar way (Rodriguez et al., 2015a, 2014, 2015b; Becker et al., 2014; Rasmussen et al., 2012; Schlachtberger et al., 2016; Hagspiel et al., 2014). But the potentially crucial role of changes in climatic conditions have not yet been assessed in this context. The remainder of this article focuses on the quantification of impacts to the power system, a correlation analysis of the wind resource and an assessment of the larger CMIP5 ensemble to contextualize our findings.

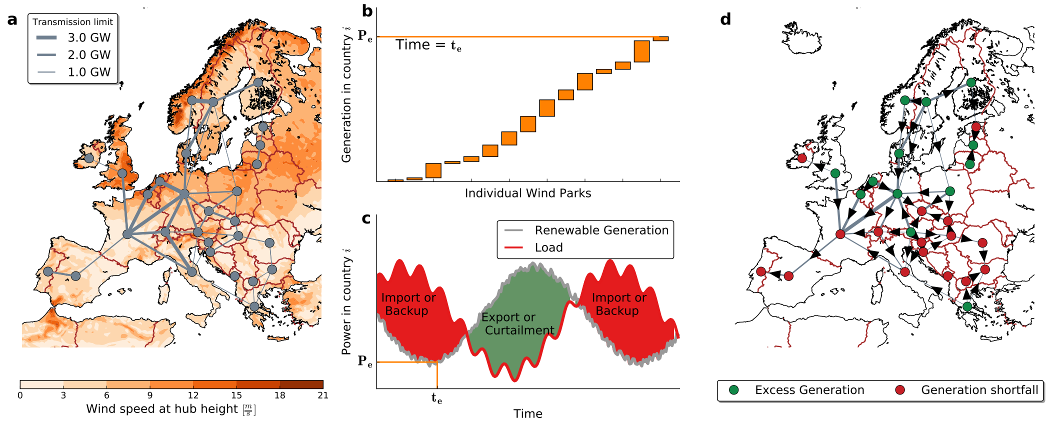

Figure 1. Approach of the study.

a) Wind fields from high-resolution climate models and the 2010/2011 Net Transfer Capacities are used as input to the model. **b)** The wind speeds are first translated into generation of individual wind parks using local wind fields . In a second step the generation is and then aggregated to a national level for each country. **c)** In combination with country-specific load data, the nodal mismatch for every country and timestep is computed. If generation exceeds the load (green area), countries can export energy until lines reach their transmission capacity. Remaining energy has to be curtailed (dumped). If generation is lower than load, electricity is imported. If importing is not an option due to transmission limits or lack of available excess energy in other countries, backup energy has to be provided by dispatchable power plants (e.g. gas turbines or other thermoelectric plants). **d)** We assume a controllable European power transmission grid. A minimization of the total backup energy of all countries then yields a flow pattern in Europe. In the shown case, strong winds over the North Sea lead to high generation in this region while there is little generation in the southern part of Europe. Energy is hence mainly transported from the North Sea region to Southern Europe and the high transmission needs lead to an operation of almost all lines at their maximum.

Table 1. Periods are chosen to contain 20 years in order to capture natural variability of the climate system on a multi-year timescale while still ensuring that elapsed time between periods is long enough to consider them distinctly. Since GCMs do not reproduce natural variations synchronously (Farneti, 2017), robust signals found in the ensemble are very unlikely to be rooted in natural variations with a recurrence time of a couple of decades (such as the Atlantic Meridional Oscillation or the North Atlantic Oscillation; see Peings and Magnusdottir (2014) for a discussion of their role in mediating atmospheric conditions). Periods used in this study. The reference period ref ends before 2005 because GCMs in CMIP5 are driven by historic emissions only until this date and follow different representative concentration scenarios afterwards.

Period name	t_{start}	t_{end}
ref	1985	2004
midc	2040	2059
endc	2080	2099

3 Results and Discussion

3.1 Energy: Increasing backup needs energy

A cost-efficient way of power balancing is given by trans-national im- and exports. Remarkably, we find that strong climate change impedes the potential of this balancing measure in most of Europe (cf. Fig. 2). We report that backup needs energy in Europe increases under strong climate change by the end of the century. This finding is robust across all EURO-CORDEX ensemble members. The increase implies more excess energy and also more curtailment since we consider a scenario where 100% of electricity is generated from renewables on average. Since we consider a scenario where 100% of electricity is generated from renewables on average, an increase of backup energy is accompanied by an increase of excess energy which has to be curtailed.

To uncover this effect we simulate backup needs energy for different scenarios of the development of the transnational grid quantified by the Net Transfer Capacities (NTCs). We allow for a homogeneous scaling of transmission capacity by multiplying NTCs with a factor α. Without any grid, approximately 45 % of the wind-energy is produced at the wrong time and thus has to be curtailed and backed up later on. A strong grid extension ($\alpha \gg 1$) clearly reduces total balancing needs backup energy to about 27% (cf. Fig. 2a). However, all models report an increase of backup energy at the end of the century. The the effect of climate change is almost independent of a grid extension: The absolute increase of backup energy until end of century is largely independent of the expansion coefficient α for three out of five models (cf. Fig. Fig. 2b). Hence, the relative increase of backup needs energy paradoxically becomes even more pronounced for a strongly interconnected Europe (cf. Fig. Fig. 2c). Highly connected systems can suffer from an increase of backup needs energy of up to 7%. There is considerable inter-model spread regarding the magnitude of change which varies by up to one order of magnitude depending on the climate model (see Fig. 2b, $\alpha = \infty$). In particular, changes for CNRM are generally weak and HadGEM2 features only a slight overall increase with grid expansion. But remarkably, all models agree on the sign of change at the end of the century such that we consider the direction of change very likely.

In conclusion, we find that the effectiveness of transnational balancing decreases due to climate change. This decrease is due to more homogeneous wind generation as we will show in the climate section of this paper. Moreover, a control simulation including PV generation from Pfenninger and Staffell (2016) yields similar results although the magnitude of change is reduced by roughly a factor of 2 and only 4 out of 5 models agree (cf. Supplementary B). Results are barely sensitive to changes in the load timeseries as an assessment using constant loads reveils reveals (cf. Supplementary C).

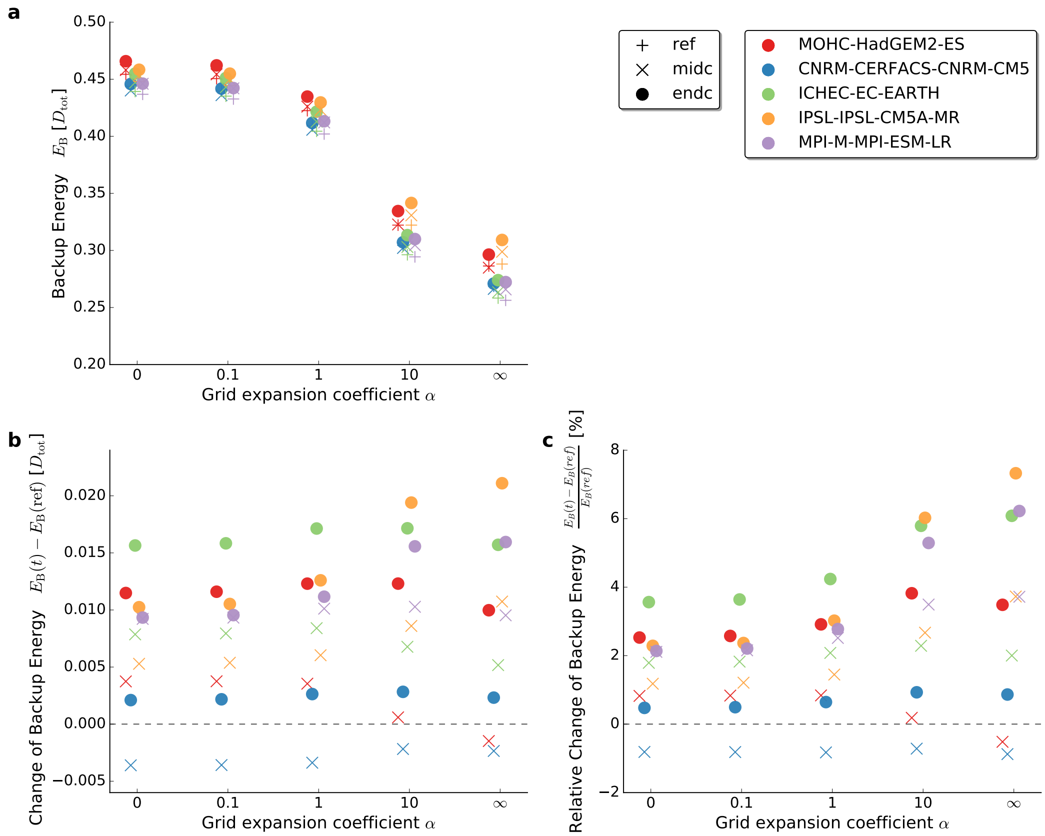

Figure 2. The impact of climate change on backup energy under different grid expansion scenarios. Different realizations of the European inter-state grid expansion are given by the grid expansion coefficient α. While $\alpha = 0$ denotes the isolated case without inter-country transmission network, $\alpha = 1$ reproduces the configuration as of today and $\alpha = \infty$ represents unlimited European transmission. Different markers refer to distinct 20 year time periods (see Table 1), colors denote different climate models. **a)** Backup energy as a function of grid expansion expressed in units of the total European load $D_{\text{tot}} = \int \sum_i D_i(t)dt$. **b)** Absolute change of backup energy by the end of the century. **c)** Relative change of backup energy by the end of the century.

a) Backup energy decreases monotonously with grid expansion. Without any grid, approximately 45 % of the wind-energy is produced at the wrong time and thus has to be curtailed and backed up lateron. This number can be theoretically reduced to roughly 27% by grid extension.

b) All models report an increase of backup energy at the end of the century. This increase is approximately independent of the grid expansion for 3/5 models. For the other two models the increase is even more pronounced for a strongly interconnected grid (large α).

c) The relative change of backup energy features a steeper increase with grid expansion as compared to **b**. Highly connected systems can suffer from an increase of backup needs energy of up to 7%.

3.1.1 Spatial distribution of Mismatch contributions

To obtain a more detailed view, we evaluate trans-national balancing potentials separately for each country. We calculate the likeliness that a given country has a local scarcity ($M_i < 0$) while Europe as a whole suffers from a lack of generation ($\sum_i M_i < 0$). This corresponds to events where a country would favor importing electricity but can not due to a continent-wide scarcity. These events require conventional backup even in the case of unlimited transmission infrastructures and thus give a lower bound for backup needs energy. The approach allows us to identify those countries which are most responsible for overall scarcity. Mathematically speaking, we restrict our analysis to timesteps T_i with local and Europe-wide scarcity:

$$T_i = \left\{ t : \left(\sum_j M_j(t) < 0 \text{ and } M_i(t) < 0 \right) \right\}. \tag{5}$$

The negative mismatch contribution occurence ν_i corresponds to the joint probability of country i and Europe experiencing generation shortfall at the same time:

$$\nu_i = \frac{\sum_{t \in T_i}}{N_T}, \tag{6}$$

where N_T is the number of timesteps. We define the annual energy that is lacking (i.e., generation shortfall) in country i during European scarcity as

$$L_i = \frac{\sum_{t \in T_i} |M_i(t)|}{20y}, \tag{7}$$

where we chose the absolute value of M_i for convenience of interpretation. L_i is given in $\mathrm{TWh/y}$ A high value of L_i characterizes a country which would favor to import a lot of energy during European scarcity whereas a low value of L_i indicates a country whose generation shortfall can often be balanced by imports. In order to compare values of L_i with loads, we provide country values for D_i in the Supplementary Material E. The European sum is $\sum_i D_i \approx 3100$ TWh.

Values for ν and L during the reference period are shown in Fig. 3a,b. Large consumers like Germany and France are also the dominant contributors to European scarcity in terms of missing energy (cf. Fig. 3a). The German contribution corresponds to approximately 8% of the European annual load of 3100 TWh. However, the role of these countries, for example, in comparison to Eastern Europe or Benelux, is less pronounced if only the occurrence of negative mismatch events ν is considered (cf. Fig. 3b). The reason for their strong impact on L is thus primarily rooted in the high absolute values of their mismatches rather than their frequency. Moreover, a large consumer also has a bigger influence on the Europe-wide mismatches which implies that the conditions in Eq. (5) are not independent. For example, the European mismatch can be negative because of an elevated

German mismatch and in such a situation a high contribution to L would be observed. Interestingly, there is considerable spread regarding ν in different countries (Fig. 3b). Greece and Norway contribute the least often to European scarcity (less than 40%) while Central Europe contributes around 50 - 60 % of the time.

Next, we focus on changes until the end of the 21st century

$$\Delta\nu_i = \nu_i|_{\text{endc}} - \nu_i|_{\text{ref}} \text{ and } \Delta L_i = L_i|_{\text{endc}} - L_i|_{\text{ref}}. \quad (8)$$

In France, Benelux, Scandinavia, the British Isles and most countries in Central Europe the negative mismatch contribution occurence ν and the respective negative energy contribution L increase (cf. Fig. 3c,d). In these countries it becomes more likely that a Europe-wide scarcity coincides with a local scarcity and the amount of required backup energy increases. In turn, these countries can not alleviate the overall shortage by exporting excess generation. This points to a stronger homogeneity of wind power generation in Central Europe which is discussed in more detail below. An increase of the occurence ν can also be observed for Eastern and South Eastern Europe, excluding Greece, with high inter-model agreement (cf. Fig. 3d). However, these increases are weak in terms of energy contributions (cf. Fig. 3c).

An opposite trend is observed in Spain, where transnational balancing is facilitated as negative mismatch contributions L become weaker (cf. Fig. 3c). At the same time, models generally disagree on the sign of change regarding $\Delta\nu$ (cf. Fig. 3d). Combined, this indicates weaker but not less frequent negative contributions of Spain. Moreover, Greece shows favourable changes for the European system in terms of energy contributions and occurences with a high inter-model agreement (cf. Fig. 3c,d). This finding is particularly interesting as Grams et al. (2017) show that a combination of wind parks allocated in the North Sea and the Balkans allows to reduce volatility substantially under current climatic conditions. Based on our results, this positive effect from incorporating the Balkans would further be enhanced under strong climate change.

We stress that our findings do not refute the efficiency of transmission grid expansions in general. In any case backup needs energy decreases monotonously with the grid expansion, but the magnitude of the decrease is subject to climatic conditions. Furthermore, we assume a homogeneous expansion of the grid, although an optimal system design will probably lead to heterogeneous grid expansions and heterogeneous allocations of generation capacities. Our results suggest that such an optimal system will include stronger interconnections to Spain and Greece to reduce backup needs energy . Also on a country level, certain extensions can be incentivized while others are downgraded. For instance, for France it can become more favorable to extend the connections to Spain rather than to Germany (cf. Fig 3c). Despite that and in light of regulatory and strong social acceptance issues regarding grid extensions (Battaglini et al., 2012), we consider a future grid which resembles the current one in its fundamental characteristics a reasonable first guess.

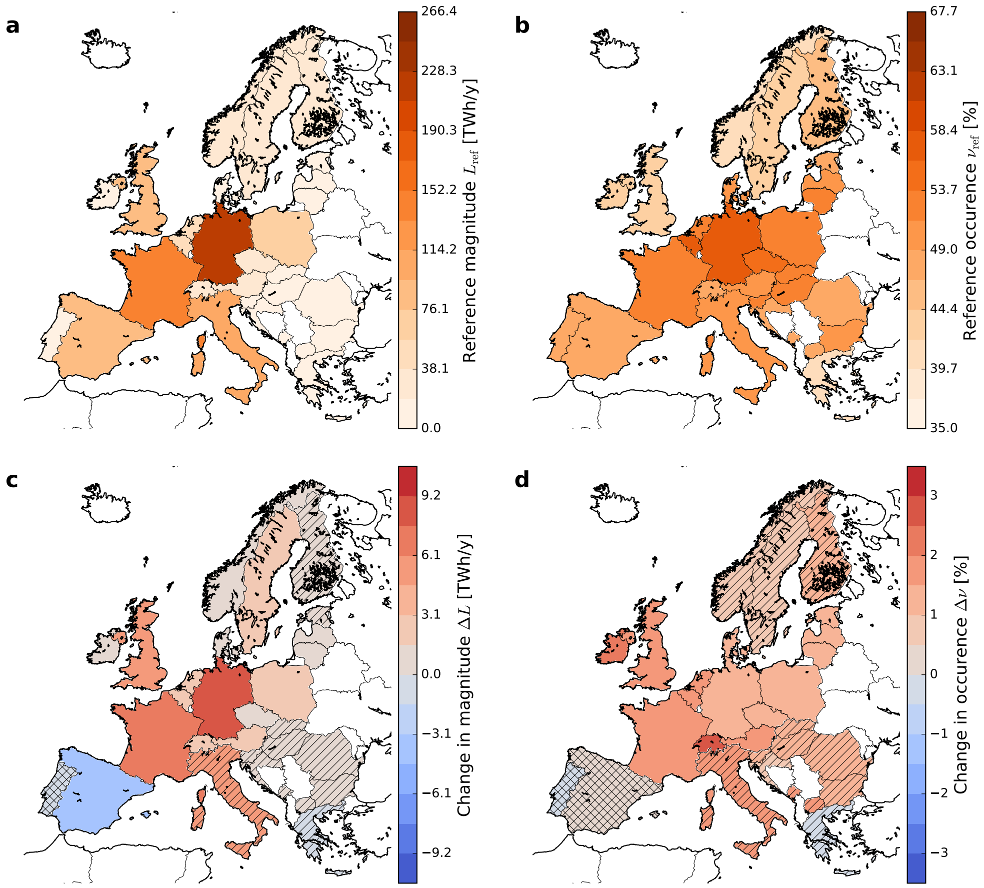

Figure 3. Country contributions in times of overall and local generation shortfall and their change until end of century. Values denote the inter-model mean. Hatches indicate inter-model agreement as follows: no hatches indicate perfect agreement on sign of change, striped: 4 out of 5 models agree, crosses: less than 4 agree. **a)** Lacking Energy L_{ref} during local and overall scarcity in the reference period (see Eg. (7)). **b)** Simultaneous occurence of local and overall generation shortfall ν_{ref} (see Eq. 6). **c)** & **d)** show changes of the quantities given in **a)** & **b)** until end of century (see Eqs. 8). Red colours denote unfavourable changes (stronger or more frequent contribution of a country to overall scarcity) while blue colors denote favourable changes.

3.2 Climate: Increasing correlations of the wind resource

As reported above, we find an increase of backup needs energy due to strong climate change in a wind-powered electricity system. This increase is solely rooted in changes of the wind resource since all other parameters are kept constant. In order to single out climate change induced alterations, we fix the technological parameters such as hub heights or turbine efficiencies, and we do not account for changes in the consumption such as load shifting or sector coupling throughout the 21st century.

For the identification of changes in the spatial wind patterns, we perform a correlation analysis over 20 year time-spans of wind speeds (see Table 1). We use Pearson correlation on the highest spatial scale, i.e. we correlate every grid point to all others instead of aggregating the wind fields first. Hence, the full spatial detail of the downscaled climate data is taken into consideration. In order to visualize results, correlation values are averaged on country level in the next step. To highlight long-term trends, we only show correlation changes between 2080-2099 (endc) and 1985-2004 (ref):

$$\Delta R_{\text{endc}}(\text{A,B}) = R_{\text{endc}}(\text{A,B}) - R_{\text{ref}}(\text{A,B}), \tag{9}$$

where $R_{\text{period}}(\text{A,B})$ denotes the average of all point-to-point correlations between country A and country B in a given period. The computation is repeated for all possible combinations (A, B). We calculate $\Delta R_{\text{endc}}(\text{A,B})$ for each climate model separately and show the model mean if not stated otherwise.

To reveal general patterns, we first consider the average correlation change of a fixed country A by averaging Eq. (9) over all countries B excluding A (cf. Fig. 4). There is a general tendency towards higher correlations of wind speeds for Central Europe in the ensemble mean. This change is most pronounced in Germany, Switzerland, Benelux and Ireland. Decreasing correlations only occur at the fringes of the continent and they are strongest in Portugal and Greece. Positive correlation changes occur in most countries and the maximum positive change is approximately three times larger in magnitude than the maximum negative change. Interestingly, the overall pattern is similar to the mismatch contribution analysis (cf. Fig. 3). This similarity is not a trivial finding since the mismatch contribution analysis accounts for the non-linear turbine power curve and the collective behaviour of the entire electricity grid while the correlation analysis is solely based on wind speeds. Summarizing, we find more homogeneous wind conditions over most of the continent while the fringes decouple slightly. Results for mid century are weaker but clearly similar (cf. Supplementary Fig. 12).

Assessing pairwise correlation changes between countries, we find that the correlation increase over Central Europe has at least a high agreement in the EURO-CORDEX ensemble (cf. Fig. 5). Some country combinations (e.g. DE-CZ, FR-CZ, BE-GB, FR-NL) even show robust trends. For example, in Germany the correlations to all neighbour contries plus the British Isles and Eastern Europe increase with high agreement. The importance of this finding is strengthened by the fact that Central Europe plays an important role for the power system: Germany, France, Great Britain, Poland

and Benelux account for more than half of the European load. Correlations between Germany and Greece decrease with high model agreement. In contrast, changes between Germany and the Iberian Peninsula, Italy and Norway are uncertain.

The decoupling of Portugal and Greece which is found in the aggregated plot (Fig. 4) is only robust in a few country combinations and models disagree regarding some important pairs (e.g. PT-DE, PT-FR, PT-GB or GR-IT, GR-UK or ES-FR, ES-GE). The uncertainty with respect to the correlation changes between these countries is thus high.

However, a robust trend is found in Scandinavia, where Norway, Finland and Sweden become higher correlated. This change partly also holds for the Baltic region. At the same time Scandinavia decouples robustly from some parts of Southern Europe (e.g. SE-GR, NO-ES). In the context of large scale European grid expansions, these alterations might enhance the value of high-voltage direct current (HVDC) lines between these distinct regions.

Correlation increases in Scandinavia are also robust in the middle of the century (cf. Supplementary Fig. 13). However, inter-model agreement for correlation increases in Central Europe is lower albeit the overall pattern is still conceivable. The decoupling of Portugal and Greece can be seen in the inter-model mean while agreement across models is rare.

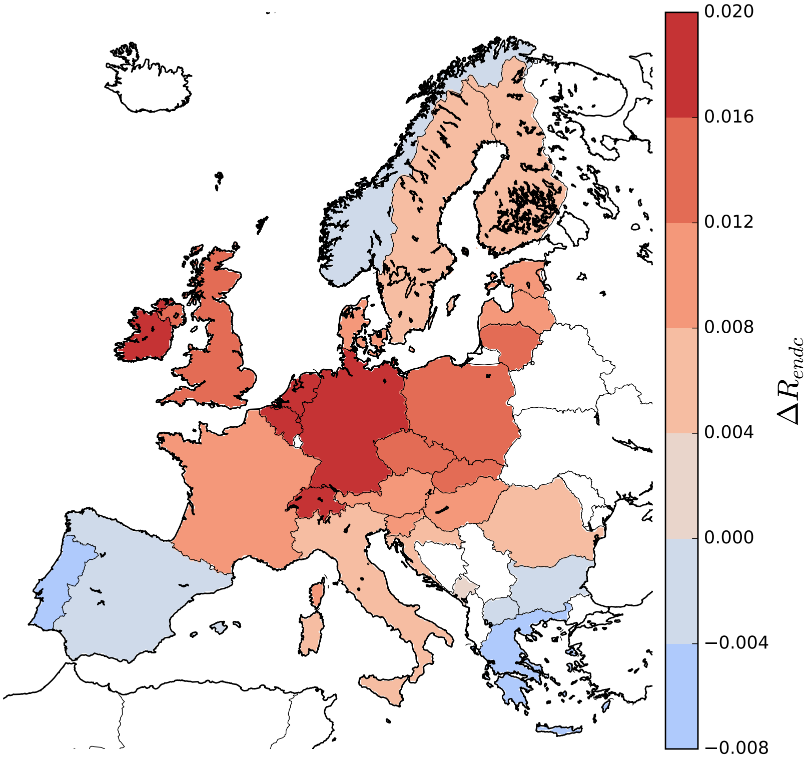

Figure 4. Correlation changes of wind timeseries averaged over all models (difference between end of century and reference correlations). An increase of spatial correlation over most of Europe is found which hints to more homogeneous wind conditions. This increase is most pronounced in the Central European region. However, at the margins of the continent correlation decreases are found. A more detailed assessment, which in particular addresses inter-model spread, is shown in Fig. 5.

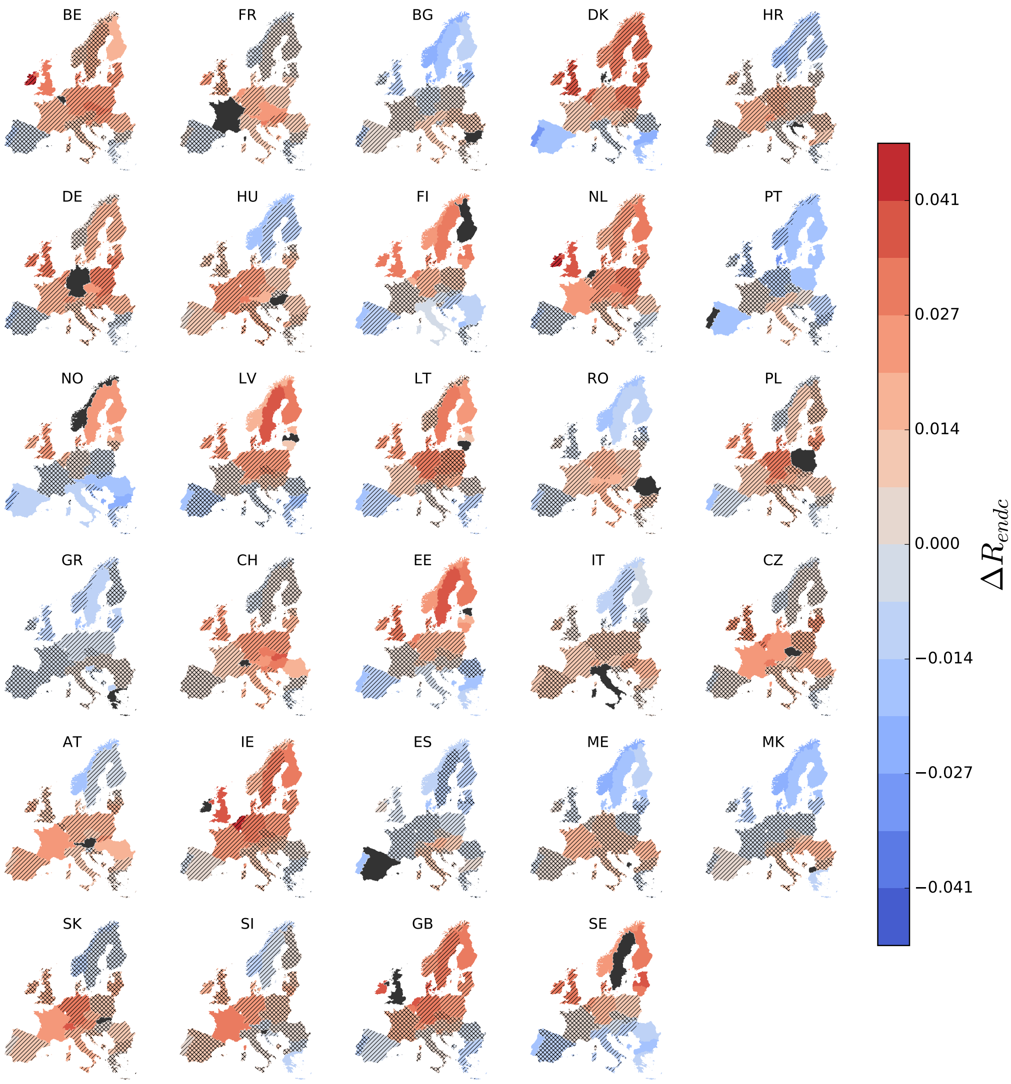

Figure 5. Country-specific change of wind speed correlations at the end of the 21st century including inter-model agreement. Colors denote the model-average correlation change of a country to the reference country (highlighted in black and given in the respective heading). Hatches indicate inter-model agreement as follows: no hatches indicate perfect agreement on sign of change, striped: 4 out of 5 models agree, crosses: less than 4 agree.

3.3 Climate: Complementing EURO-CORDEX with CMIP5 using Circulation Weather Types

The EURO-CORDEX dataset includes only a 5-member subset of all CMIP5 GCMs and might thus not be representative for the entire CMIP5 ensemble. Moreover, subgroups of GCMs can be biased in the same way since they did not develop separately, but along the same lines. The most drastic example is the sharing of code by CNRM and EC-EARTH, which are both part of the EURO-CORDEX ensemble and run the same atmosphere module (Knutti et al., 2013).

Uncertainty in climate projections has been argued to stem from three main sources: (1) natural variability, (2) model uncertainty and (3) scenario uncertainty (Hawkins and Sutton, 2009). In some situations the choice of initial conditions also contributes substantially (Hawkins et al., 2016). We neglect scenario uncertainty by design of this study since we only focus on the sensitivity to strong climate change (RCP8.5). As the importance of natural variability decreases with the time intervals averaged over, model uncertainty is likely to be the dominant source of uncertainty here.

In order to rule out the possibility that our findings are biased due to the (arbitrary) choice of GCMs that were downscaled for EURO-CORDEX, we follow a statistical-dynamical approach which was developed by Reyers et al. (2015, 2016) to downscale a large CMIP5 ensemble for wind energy applications. This approach is based on a circulation weather type (CWT) classification methodology (Jones et al., 1993). Daily mean sea level pressure (MSLP) values at 16 GCM grid points around a central point located in Germany are used to assign the near-surface atmospheric flow over Europe to either a directional flow (north, northeast, east, ...) and/or a rotational flow (anticyclonic, cyclonic). Aside from the direction of the atmospheric flow a f-parameter is calculated, which is representative for the instantaneous pressure gradient and thus for the general wind speed conditions over Germany and the surrounding countries.:

$$f = \sqrt{dP_z^2 + dP_m^2}, \tag{10}$$

where dP_z is the mean pressure gradient in East-West direction (zonal component) and dP_m is the mean pressure gradient in North-South direction (meridional component). f-parameters from below 5 hPa per 1000 km (weak MSLP gradient and thus low wind speed conditions) up to 45 hPa per 1000 km (strong MSLP gradients and thus high wind speed conditions) were found. Reyers et al. (2016) demonstrated that such a CWT classification provides a suitable and effective basis for wind energy applications on the regional scale and therefore enables the consideration of a large CMIP5 ensemble in future projections.

Analyzing the five individual GCMs contributing to the EURO-CORDEX ensemble reveals a link between the CWTs and the backup energy needs derived from dynamically downscaled data (see Eqs. 1, 2, 3). We find that backup needs energy decreases monotonously with increasing f-parameter (cf. Fig. 6a,b). All models in the EURO-CORDEX ensemble agree on this result which is also physically plausible as the pressure gradient drives the atmospheric circulation. This statement holds for Germany and its neighbors and for Europe as a whole. We see this as evidence that the

CWT analyses in this particular case can be applied to the entire continent in the sense that the f-parameter is a reasonable proxy for the European backup need energy.

The majority of CMIP5 models (16 out of 22) predicts an increase of events with low f-parameter by the end of the century (cf. Fig. 6c). Following the likelihood classification developed for the latest IPCC report (Mastrandrea et al., 2010), it is thus *likely* that low f-parameters become more abundant. This trend originates mainly from more frequent anticyclonic pressure configurations (cf. Fig. 7). For this CWT, spatial homogeneity of the wind resource is higher as compared to all other CWTs (cf. Supplementary Fig. 14). In such a homogeneous situation, it is plausible that backup needs are energy is elevated since countries are more likely to experience shortfall of generation simultaneously. In contrast, medium $(10 \leq f[hPa/1000km] \leq 15)$ and high $(15 \leq f[hPa/1000km] \leq 20)$ f-parameters are *likely* to occur less frequent since 17 models agree on these signals. We thus conclude that the majority of CMIP5 models agrees with the main finding of increasing backup needs energy .

The larger CMIP5 ensemble also allows for an assessment of the EURO-CORDEX ensemble's input data. We report that the GCMs contributing to EURO-CORDEX are within the spread of the remaining CMIP5 ensemble (exception HadGEM for very strong f-parameters) and are thus generally representative for the larger ensemble (see Fig. 6). However, they also show comparably strong changes in the occurence of specific f-parameters. The CMIP5 overall projection regarding backup needs energy might thus be lower than results reported in this paper. In order to test this speculative hypothesis, a consistent downscaling of all CMIP5 models would be necessary, which is far beyond the scope of this article but should be tackled in future works.

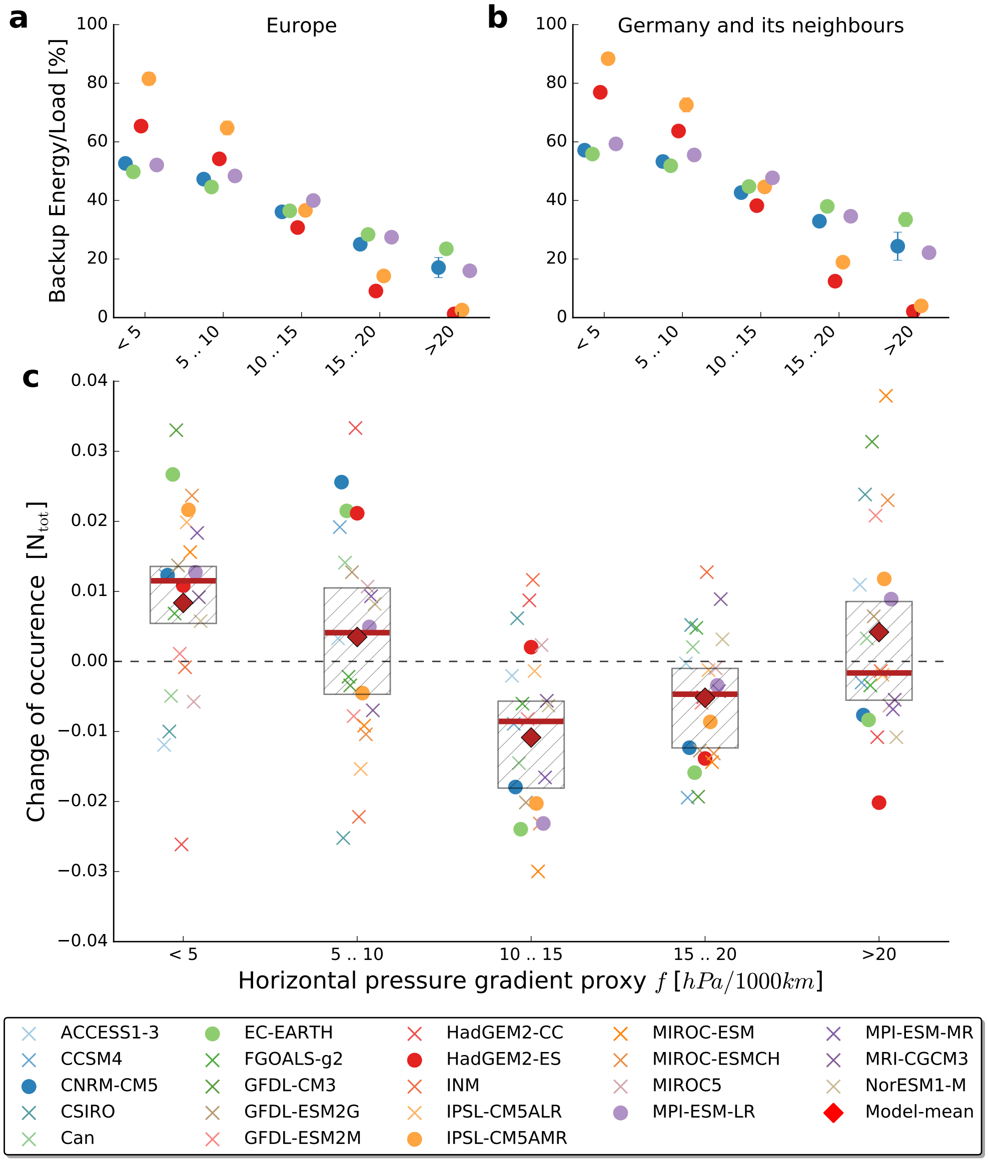

Figure 6. Backup energy and change of occurrence as a function of the f-parameter. a) Monotonous decrease of backup energy with increasing f-parameter Backup energy versus f-parameter for the entire domain. Circles denote the mean over the three considered periods for each model and errorbars indicate the standard deviation thereof. Errorbars are, however, most often smaller than the circle size. **b)** The same decline is found if only Germany plus its neighbor countries are considered. Same as **a)** but restricted to Germany and its neighbors **c)** Change of occurrence of different f-parameters. The change of occurence is computed as the difference between end of century and the reference period and is given in units of the total number of timesteps N_{tot}. Low f-parameters become more frequent by the end of the century while medium to high f-parameters occur less often. There is considerable inter-model spread, however 16/22 agree on an increase in frequency of very low pressure events ($f < 5$) and 17/22 agree on a decrease of medium pressure events ($10 \leq f < 15$). Red diamonds denote the ensemble mean, red lines the ensemble median and hatched boxes indicate the 33rd to 67th percentile. If a box lies completely above/below zero, the sign of the change can be considered as likely (Mastrandrea et al., 2010).

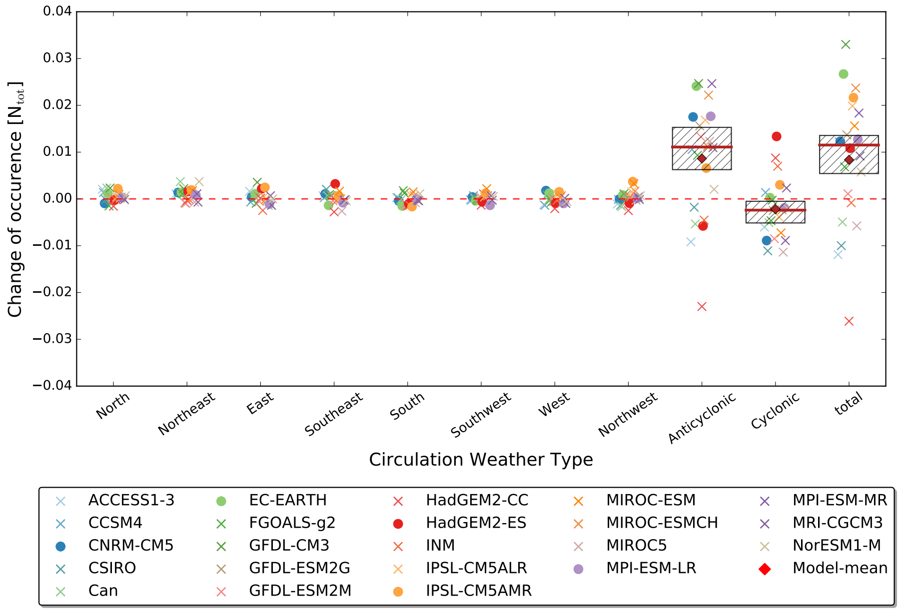

Figure 7. Changes of relative occurrence of primary CWTs with low f-parameters ($f \leq 5hPa/1000km$). Changes are differences in occurrence between end of century and the reference period and are given in units of the total number of timesteps N_{tot}. Boxes indicate the 33rd to 67th percentile and are only shown if changes are substantial. A majority of models projects more weak anticyclones while cyclonic CWTs occur less often (both findings are likely). In total, most models project an overall increase of the occurence of CWTs with low f-parameters. This increase is dominantly rooted in more frequent anticyclonic CWTs. Red diamonds denote the ensemble mean and red lines denote the ensemble median.

4 Conclusions

A future highly-renewable electricity system will be governed by weather conditions. If mankind fails to reduce carbon emissions fast, climate change will impede the operation of a wind-driven system in Europe. This conclusion is based on three separate lines of evidence.

1. A coarse-scale electricity model fed with EURO-CORDEX climate data shows robust increases of backup needs energy.

2. Spatial correlations in wind timeseries in EURO-CORDEX data across Central Europe are found to increase. Countries are thus more likely to experience generation shortfall simultaneously.

3. Building upon a statistical-dynamical downscaling technique and a 22-member CMIP5 ensemble we find a likely increase of Circulation Weather Types with low f-parameters. They are associated with low Europe-wide wind generation.

It has to be stressed that results are for the end of the 21st century and based on a strong climate change scenario (RCP8.5). They should be thought of as a sensitivity test. Moreover, While the increases of backup energy are robust yet , they are also restricted to relative increases of 87% (cf. Fig. 2). A fully-renewable electricity system will hence not become unfeasible due to catastrophic changes.

In the emerging field of linking energy and climate research, many additional questions are to be addressed in order to deliver a more holistic assessment. We simulated a wind-driven electricity system and performed a control simulation with a fixed share of PV. Timeseries for the latter were taken from a validated dataset based on reanalysis data (Pfenninger and Staffell, 2016). Ideally, future works would assess the combined effects of climate change on wind and solar generation. They could also include concentrated solar power since this technology bears advantages for system integration (Pfenninger et al., 2014). Load-shifting, sector-coupling and storage are further key words for more detailed assessments.

In terms of climate modeling output, a larger high-resolution ensemble is desirable which in particular contains multiple Regional Climate Models (RCMs). The next generation of CORDEX is planned to deliver such data (Gutowski Jr. et al., 2016) and will hence allow for an inclusion of RCM-spread in future assessments. It will also facilitate similar assessment for other world regions as spatial extent will be expanded.

Contributions

Ja. W. performed the simulations, analyzed the data, produced all figures and wrote most of the manuscript. D. W. conceived and supervised the research and contributed to the writing, in particular regarding the electricity system. M.R. supplied the CWT analysis and wrote parts of the CWT chapter. All authors contributed ideas, gave feedback and helped to improve the manuscript.

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Supplementary Material

A) Detailed methodology

Adopting the approach of Tobin et al. (2016), we use near-surface wind speeds 10 meters above the ground. Assuming a power-law relationship for the vertical wind profile, the velocity at hub height H is obtained as

$$v_H = v_{10\text{m}} \cdot \left(\frac{H}{10}\right)^{\frac{1}{7}} \tag{11}$$

and we chose $H = 80$m.

The conversion of wind speeds into renewable generation is performed using a simple power curve

$$P(v_H) = P_0 \begin{cases} 0, & \text{if } v_H < v_i \text{ or } v_H > v_0 \\ \frac{v_H^3 - v_I^3}{v_R^3 - v_I^3}, & \text{if } v_I \leq v_H < v_R \\ 1, & \text{if } v_R \leq v_H < v_0 \end{cases} \tag{12}$$

where v_H denotes wind velocity at hub height and $v_I = 3.5$ m/s, $v_R = 12$ m/s, $v_0 = 25$ m/s denote the cut-in, rated and cut-out velocity of the wind turbine, respectively. We assume that every wind park has a capacity $P_0 = 0.1$ GW.

If the number of wind parks per grid cell $N_{\text{wind}}(x, y)$ is known, the renewable generation in a country with area A_i is given by

$$P_i(t) = \sum_{x,y \,\in\, A_i} N_{\text{wind}}(x, y) \cdot P(v_H(x, y, t)). \tag{13}$$

Note that we assume a stationary configuration of wind parks throughout every 20 year period. Moreover, we assume that each country generates as much energy from renewables as is needed in a 20 year period ranging from t_{start} to t_{end}

$$\int_{t_{\text{start}}}^{t_{\text{end}}} P_i(t)dt = \int_{t_{\text{start}}}^{t_{\text{end}}} D_i(t)dt \tag{14}$$

Since all variables except from N_{wind} are used as input to the model, and hence are known, equations (13) and (14) can be used to determine N_{wind}. However, the solution is degenerate. In order to single out one solution, we adopt the strategy of Monforti et al. (2016) who distribute wind parks randomly at those places where the temporal average of renewable generation P is above average. Performing a Monte Carlo analysis for the deployment of wind parks, Monforti et al. found that the sensitivity of this partially random allocation procedure to changes in the actual configuration of N_{wind} is small.

Transmission

The imports/exports F_i of a country i (see Eq. (2)) depend on the incidence matrix

$$K_{i,l} = \begin{cases} 1, & \text{if line l starts in country i} \\ -1 & \text{if line l ends in country i} \\ 0 & \text{otherwise} \end{cases} \tag{15}$$

and the flows $\hat{F}_l$ along a line l

$$F_i = -\sum_l K_{i,l} \hat{F}_l, \tag{16}$$

where the minus sign stems from the (arbitrary) choice that $F_i > 0$ means imports. The flow along a line l is bound by

$$\alpha \cdot \text{NTC}_{l-} \leq \hat{F}_l \leq \alpha \cdot \text{NTC}_{l+}, \tag{17}$$

where α denotes grid expansion. The line limits $\text{NTC}_l + \geq 0$ and $\text{NTC}_l - \leq 0$ are direction dependent and the former refers to the line limit in the direction of line l as defined via the incidence matrix (15). Line limits are directional winter Net Transfer Capacities published by ENTSO-E for 2010/2011 (European Network of Transmission System Operators for Electricity, 2011).

Inclusion of PV generation

We use PV generation timeseries from Pfenninger and Staffell (2016) which is more complete than other open source datasets like Open Power System Data[1]. The data set is bias corrected and validated at around 1000 locations. We favored to use the part of the dataset which is based on MERRA over SARAH because the latter is lacking data in the first years.

We average over 30 years of data to compute a representative PV generation timeseris $PV_i(t)$ for every country i. Using a representative year is not an ideal approach since inter-year variations are artificially muted. However, the PV generation timeseries only exists for the historical period. If one was to combine PV generations from one year with wind generations from another, the result is likely to be unrealistic because the corresponding state of the climate system belonging to either the PV or wind generation would be out of phase. We thus consider our approach to be the most suitable one in this assessment.

In order to incorporate PV generation into the model, we replace the original load $D_i(t)$ in Eq. (1) with the residual load after PV generation is subtracted as

[1] http://www.open-power-system-data.org/

$$D_i(t) \rightarrow D_i(t) - \gamma \cdot PV_i(t), \tag{18}$$

where γ is chosen such that 29% of the overall generation is contributed by PV. This share has been found to be the European optimum in terms of minimizing backup needs energy in a similar setup (Rodriguez et al., 2014). The load $D_i(t)$ now represents the residual load which has to be satisfied by wind, im-/exports or dispatchable power plants. Results including PV are shown in Supplement B.

Sensitivity to load timeseries

We repeat our analysis assuming constant loads

$$D_i(t) \rightarrow \langle \hat{D}_i(t) \rangle_t, \tag{19}$$

where $\hat{D}_i(t)$ denotes monthly load data from ENTSO-E and $\langle \cdot \rangle_t$ denotes the temporal average. The goal of muting the time depency of the load is to test for the influence of the load timeseries on our modelling outcomes. Results for constant loads are shown in Supplement C.

B) Energy results including PV

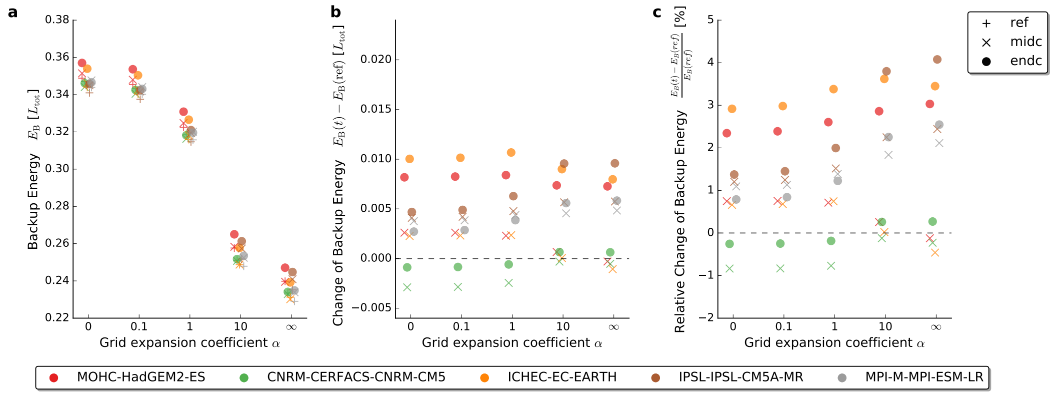

Figure 8. Same as Fig. 2, but including PV from Pfenninger and Staffell (2016).

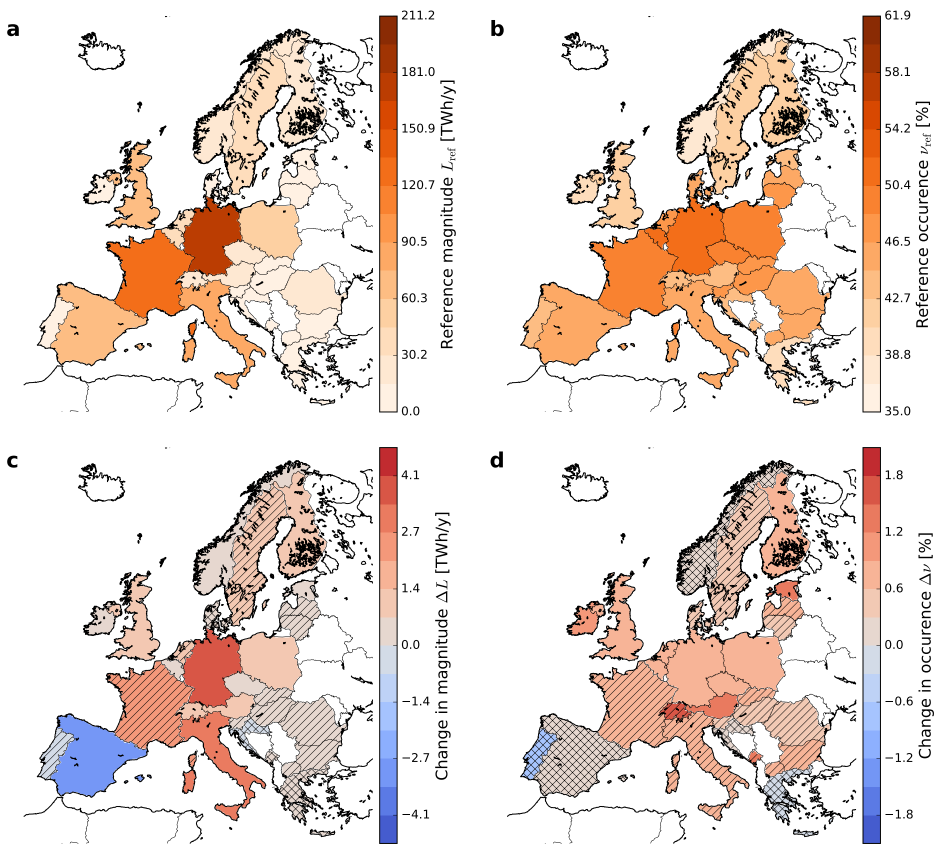

Figure 9. Same as Fig. 3 but including PV from Pfenninger and Staffell (2016).

C) Energy results assuming constant loads

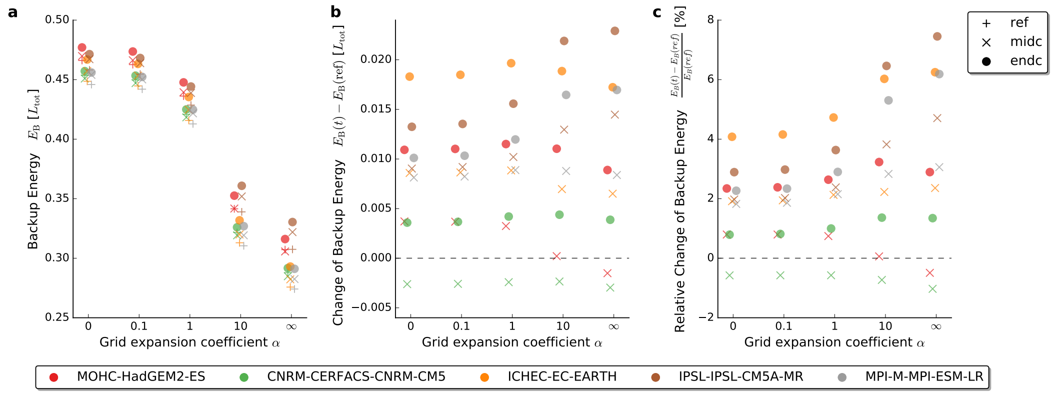

Figure 10. Same as Fig. 2, but with constant load.

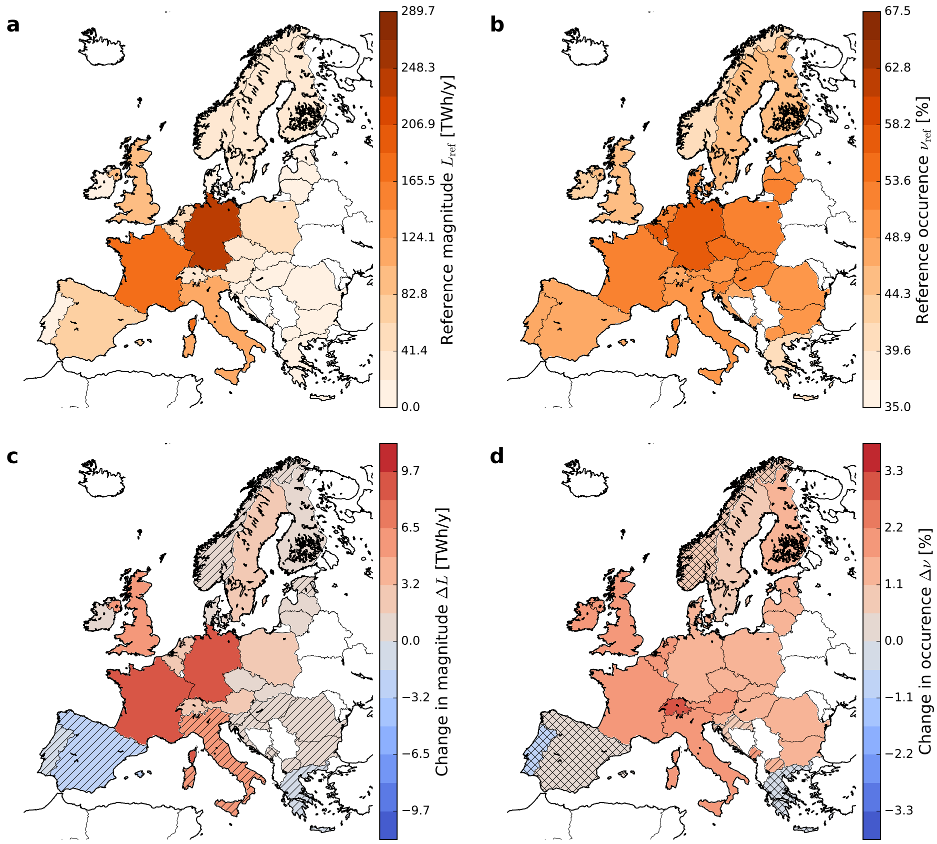

Figure 11. Same as Fig. 3 but assuming constant load.

D) Correlations by mid century

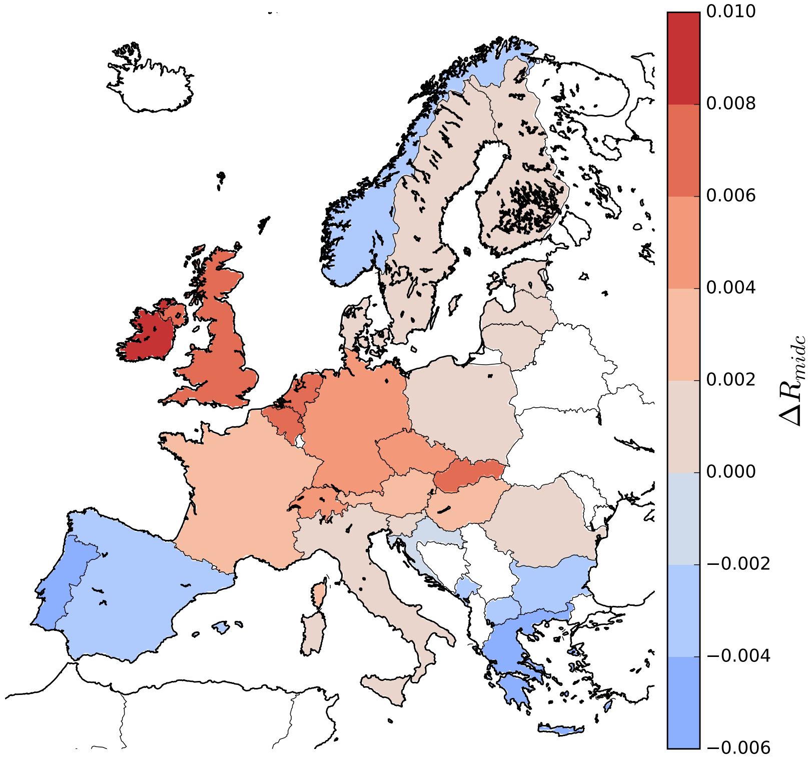

Figure 12. Same as Fig. 4 but for mid century.

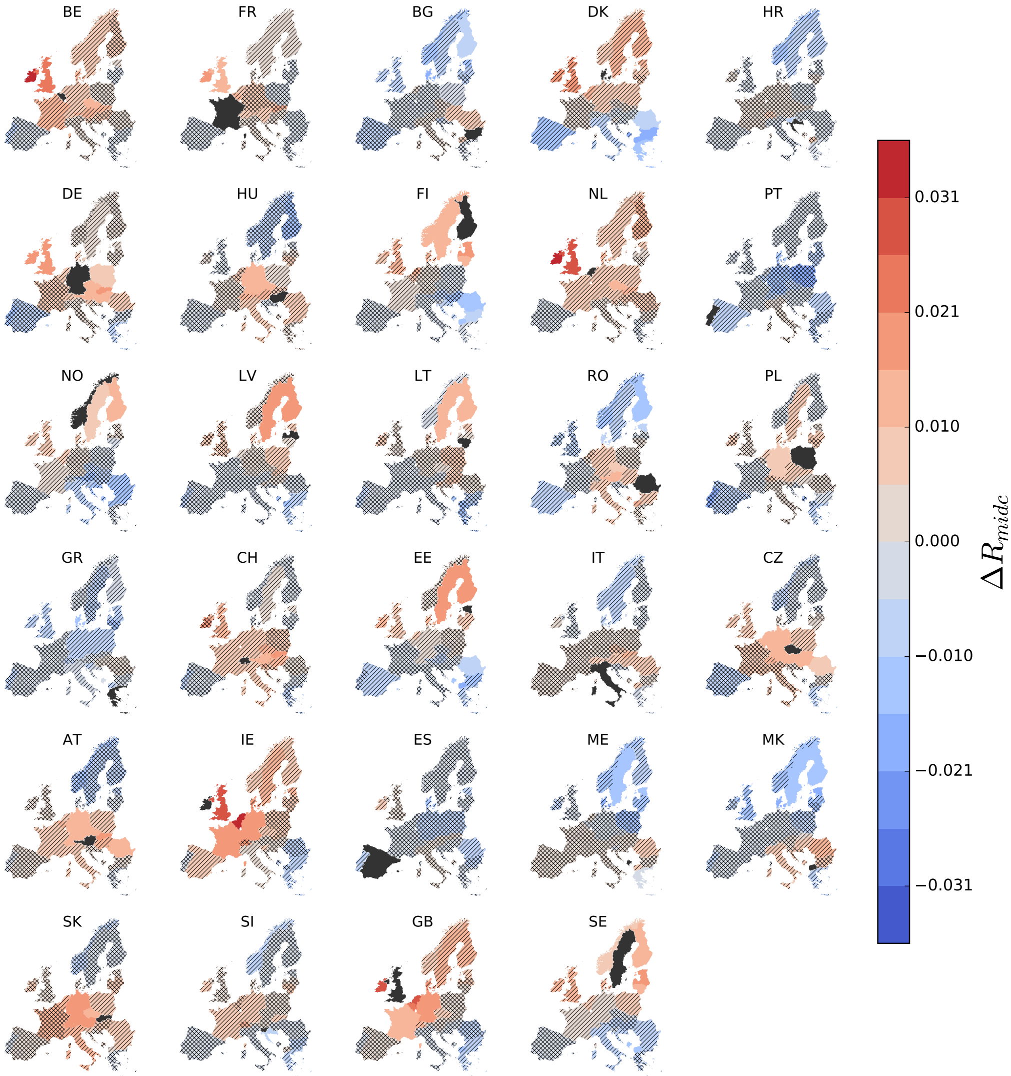

Figure 13. Same as Fig. 5 but for mid century.

E) Spatial homogeneity and CWTs

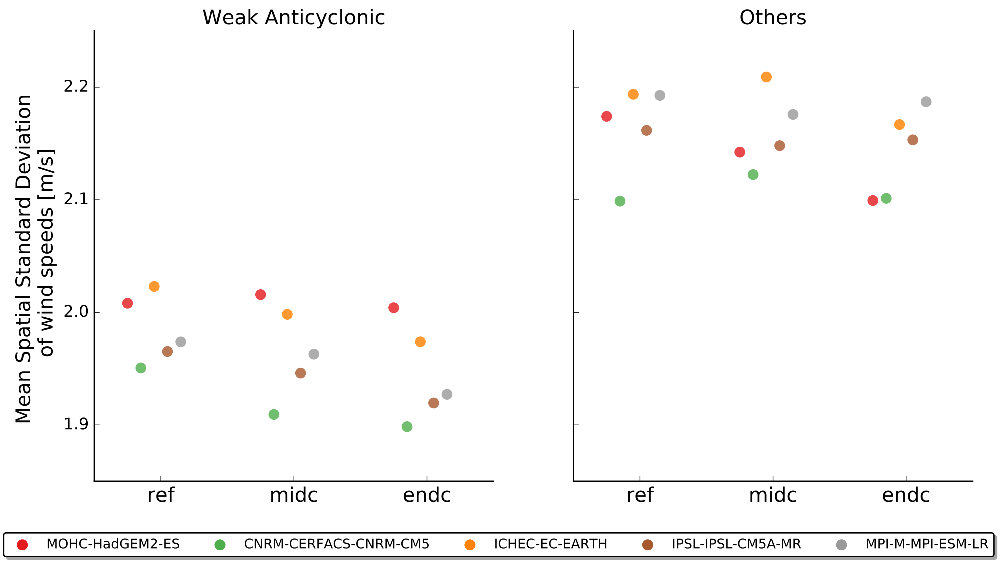

Figure 14. Mean spatial standard deviation of wind speeds over all 28 countries considered in the energy assessment. The standard deviation is calculated for each grid point seperately. The weak anticyclonic CWT has a distinctly smaller spatial standard deviation than all other situations considered together. Hence, it is characterized by more homogeneous wind fields.

F) Annual load values on country level

Table 2. Annual sums of country electricity consumption based on hourly 2015 data provided by the European Network of Transmission System Operators for Electricity (2015).

country	**country code**	**Annual load [TWh]**
Austria	AT	69.62
Belgium	BE	85.22
Bulgaria	BG	38.62
Switzerland	CH	62.06
Czech Republic	CZ	63.53
Germany	DE	505.27
Denmark	DK	33.9
Estonia	EE	7.93
Spain	ES	248.5
Finland	FI	82.5
France	FR	471.26
Great Britain	GB	282.19
Greece	GR	51.4
Croatia	HR	17.19
Hungary	HU	40.75
Ireland	IE	26.57
Italy	IT	314.35
Lithuania	LT	10.86
Latvia	LV	7.07
Montenegro	ME	3.42
Macedonia	MK	7.84
Netherlands	NL	113.25
Norway	NO	128.65
Poland	PL	149.96
Portugal	PT	48.93
Romania	RO	52.31
Sweden	SE	135.93
Slovenia	SI	13.65
Slovakia	SK	28.21
Total		3100.94