Climate change impacts on solar power generation and its spatial variability in Europe based on CMIP6

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Response to the reviewers

We appreciate the two anonymous reviewers' positive feedback on our manuscript. Below, we provide point-by-point responses to the comments.

Legends:

Italics: Reviewer comments

→ Author responses

~~Deletions in red and strikethrough~~

Additions/insertions in blue

Review 1

General comments

This paper assesses the availability of solar power for electricity production in Europe, under future emission scenarios. The authors first analyse the future change in climate variables relevant for solar power availability, as described in state-of-the-art CMIP6 climate projections. Then they use the Global Solar Energy Estimator (GSEE) to predict and analyse the change in the PV potential under a mitigation (SSP2.6) and a fossil-fuel dependent (SSP8.5) scenario.

The paper is well written, in a clear and concise manner. Data and methods are appropriate for the purpose of the study, and conclusions are supported by evidence. The paper does not add much to the existing knowledge on the expected changes of the PV potential in Europe in relation of climate change. However, it has the merit of updating the existing picture by using the last state-of-the-art climate projections, also adding the assessment of the PV power complementarity at the continental scale. I believe that this is a valuable contribution to the knowledge in the field and I recommend publication.

I have no major comments to address to the authors. However, some minor issues should be fixed before final publication. Please see my comments below.

Specific comments

L14: Please add few words to clarify how "a decrease in clear-sky radiation is overcompensated by a decrease in cloud cover".

→ Thanks for this comment. Please note that both processes affect PV generation in opposite directions: a decrease in clear-sky radiation reduces PV generation while a decrease in cloud cover increases surface solar radiation, thereby also increasing PV generation.

Changes to the manuscript:

While increased clear-sky radiation and reduced cloud cover go hand in hand in SSP1-2.6, the effect of a decrease in clear-sky radiation is ~~overcompensated~~outweighed by a decrease in cloud cover in SSP5-8.5, resulting in an increase of all-sky solar radiation.

L98: Is the role of wind speed negligible in the simulation of the PV potential in GSEE? Several authors take it into account in their computations (see e.g. the CLIMIX model by Jerez et al. 2015).

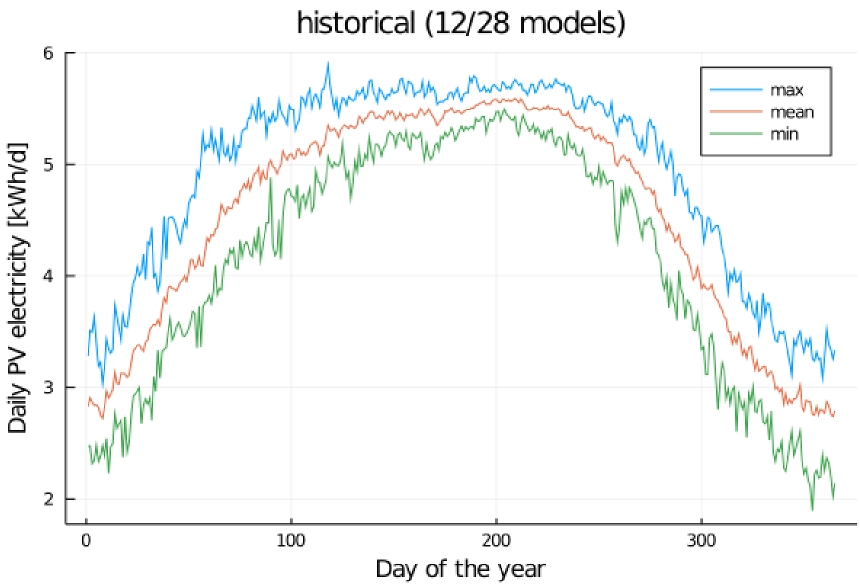
→ You are correct that GSEE does not include wind speeds in the calculation of panel efficiencies and instead adopts a relative PV performance model by Huld et al. (2010, https://doi.org/10.1016/j.solener.2009.12.002). We think that this approach is well justified in large-scale assessments for three main reasons. First, the effect of including wind speeds is small. Taking the numbers from Jerez et al. 2015 and equations 2 and 3 from their Method section, it follows that a wind speed increase of 1 m/s raises panel efficiency by about 0.75% (gamma * c4). Second, projected changes in near-surface wind speeds over the 21st century are small and of uncertain sign in many locations (e.g., Pryor et al., 2020). Third, solar panels are usually mounted close to the ground or on buildings, implying that local effects strongly control wind speeds experienced by the panels. Since we have no detailed information about these local effects and given that CMIP6 model resolution is far too coarse to resolve individual houses and the like, using CMIP6 near-surface wind speeds might well deteriorate rather than improve the result.

Addition to L101:

The effects of wind speed changes on panel efficiency are neglected due to their small magnitude and pronounced uncertainty of wind speeds at the panel location, which are strongly controlled by local effects.

L115: Computing the daily seasonal cycle by using daily climatology usually produces a very noisy seasonal cycle. Why not to add a filter (e.g. moving average) to smooth it?

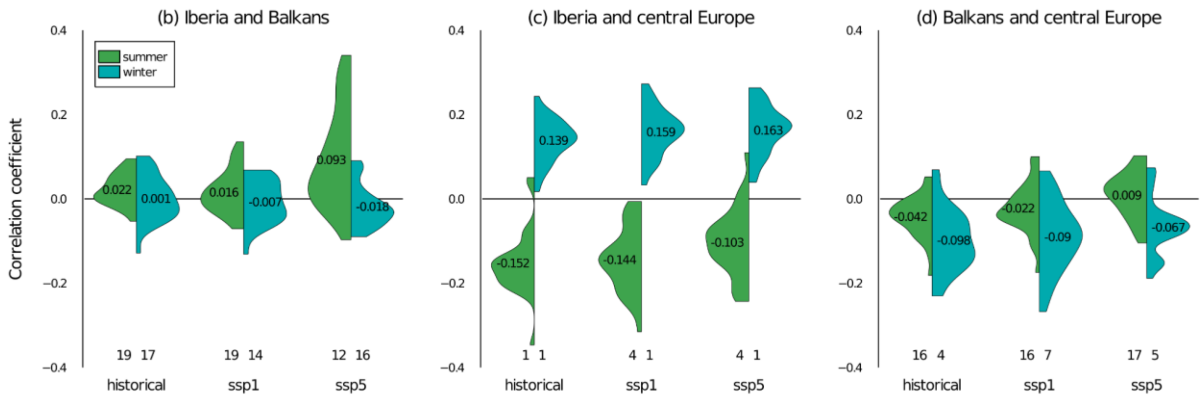
→ Daily climatology does not produce a seasonal cycle with much noise in our case. We demonstrate this by selecting 12 models that use a 365-day calendar to plot the historical 20-year seasonal cycle for PV generation in Iberia. As you can see in the Figure below, daily fluctuations are smaller than 0.1 kWh/d, while the winter-to-summer difference is around 2.5 kWh/d. This demonstrates that the mean curve is already very smooth, and it would be even smoother when using the full set of models, as was done in the manuscript



L125: I believe that also assessing the significance of correlation would add valuable information.

→ add to Fig. 6 (b) - (d):

The values below each violin part shows the number of models (out of 28) for which the null hypothesis (zero correlation) cannot be rejected at the 5% level. At the same time, the rest of the models have a statistically significant non-zero correlation.



I would also highlight in the discussion that the optimal correlation in this case is not zero, but negative correlation.

→ insert to L267:

Ideally, a negative PV production correlation of exactly minus one between two locations would guarantee stable supply of power. A small correlation close to zero would provide stable supply when many different locations are combined. Here, we found that the correlation between the Iberian Peninsula and …

L150-152 and L154-155: I believe that this lines should be at the end of the section. Also not to disrupt the narrative of the paper.

→ changes to the manuscript:

~~Associated findings for SSP5-8.5 are found to be largely in line with corresponding studies based on RCP8.5 from CMIP5 (Müller et al. 2019). For SSP1-2.6, we find qualitatively different results that to our knowledge are original and have no CMIP5 counterpart in the literature.~~ Finally, we turn from mean power production to spatio-temporal balancing of PV power production. Looking at spatial correlations of daily PV power production under present-day and future projections, we find that the balancing potential among European regions tends to decrease in the future (Sect. 3.3). Associated findings for SSP5-8.5 are found to be largely in line with corresponding studies based on RCP8.5 from CMIP5 (Müller et al. 2019). For SSP1-2.6, we find qualitatively different results that to our knowledge are original and have no CMIP5 counterpart in the literature.

Section 3.1: Concerning the changes in cloud cover, which are the key element for explaining the changes in PV potential, can you also discuss possible links with changes in atmospheric circulation? E.g. NAO, jet-stream, storm-track.

→ Possible addition to L302:

The relationship between the total cloud cover over the Iberian Peninsula and the dominant modes of atmospheric circulation variability during summer is weaker than during winter due to clouds of a more convective origin in the warm season (Sanchez-Lorenzo et al., 2009). Jerez et al. (2013) show that negative North Atlantic Oscillation (NAO) phases strengthen the westerly winds over Iberia and enhance cloudiness there, thereby diminishing the solar potential by 10 to 20 %.

- Jerez, S., Trigo, R.M., Vicente-Serrano, S.M., Pozo-Vázquez, D., Lorente-Plazas, R., Lorenzo-Lacruz, J., Santos-Alamillos, F., Montávez, J.P., 2013. The Impact of the North Atlantic Oscillation on Renewable Energy Resources in Southwestern Europe. J. Appl. Meteor. Climatol. 52, 2204–2225. https://doi.org/10.1175/JAMC-D-12-0257.1
- Sanchez-Lorenzo, A., Calbó, J., Brunetti, M., and Deser, C.(2009), Dimming/brightening over the Iberian Peninsula: Trends in sunshine duration and cloud cover and their relations with atmospheric circulation, *J. Geophys. Res.*, 114, D00D09, doi:10.1029/2008JD011394.

L226: What do you mean with "climatic boundary conditions"? Please explain.

→ insert:

To conclude, we find that mitigating emissions according to the SSP1-2.6 improves the climatic boundary conditions for PV, i.e., the availability of total horizontal irradiance, ...

L236: This is just a comment, not a request. I feel that the "unfortunately" is not appropriate in the context of a scientific/technical paper, which in my view should be as neutral as possible. However, I don't want to question your style, nor ask for modifications, just stimulate reflection.

→ change to:

~~Unfortunately~~However, we find that PV generation becomes more uniform in both SSP scenarios;

L248-250: You could also refer to the possibility of complementary PV-wind power production -> https://journals.ametsoc.org/view/journals/apme/56/1/jamc-d-16-0031.1.xml

→ We refer to this aspect in L109-111: The evolution of the seasonal cycle is of high practical relevance, as combining wind and solar power allows smoothing generation variability throughout the year (Heide et al., 2010). Optimal shares of wind and solar power would thus change if the seasonal cycle of generation changes.

Insert to L248 before "Moreover": These changes might affect the possibility of complementary power production from the PV and wind sources over Europe during summer and winter (Heide et al., 2010; Miglietta et al., 2017).

L254: I'm wondering why central Europe also includes the Alpine region, which is supposedly not suitable for PV power production.

→ Why is the Alpine region not suitable for PV power production? For example, the Swiss Ministry for Energy reports that the "photovoltaic sector has increased strongly in absolute terms since 2010" and now "contributes about 52 percent to electricity production from new renewables" [Swiss Federal Office of Energy, Energy Strategy 2050, Monitoring Report 2020]. Given that Switzerland is aiming for around 11 TWh of non-hydropower renewables (roughly a tripling from today), PV will soon be an important contributor in absolute terms.

Figure 6: I find that this figure is poorly discussed. Especially panel (c) showing interesting results should be further commented.

→ Modify L267 - 276 to three separate paragraphs, each dealing with one pair:

The correlation between the Iberian Peninsula and the Balkans is generally close to zero in the historical period (below 0.025 in absolute terms on average across all models, and ~~below 0.4~~ within ±0.1 ~~in absolute terms~~ for ~~any~~ nearly all individual models).

Daily PV under-production in one region is thus often accompanied by excess production in the other region, implying that, in principle, mutual production buffering on daily time scales is possible. Turning to the future ~~scenarios~~, average correlations across all models ~~change but little~~ experience only a slight increase in summer in SSP1-2.6 and a slight decrease in winter for both SSP scenarios. However, a few models suggest for summer in SSP5-8.5 substantial changes with correlations reaching up to 0.~~2~~4, implying reduced buffering potential.

The correlation between Iberia and central Europe suggests that the potential for PV electricity balancing between these two regions is greater in summer than in winter, as indicated in the distinctive negative and positive correlations in the respective season. Between these regions, the average correlations increase mildly in both seasons from the historical period to SSP1-2.6 to SSP5-8.5, implying a slight reduction in buffering potential.

Between the Balkans and central Europe, less difference between summer and winter is visible. The correlation is generally below zero and generally lower in winter than in summer. We observe increased average correlations in SSP scenarios for both seasons, compared to the historical period. These increases in correlations between central Europe and Iberia as well as between central Europe and the Balkans are the regional equivalent of the correlation changes seen over the continent (Fig. 5).

Moreover, you could give an indication on how to discern between "good and bad" correlations.

→ insert to L267, see one previous comment

Ideally, a negative PV production correlation of exact minus one between two locations would guarantee stable supply of power. A small correlation close to zero would provide stable supply when several different locations are combined. Here, we found that the correlation between the Iberian Peninsula and …

L268: I see mean correlation is 0.022 and 0.001 on average and the PDF is between ±0.1 circa. I don't understand why you mention 0.05 and 0.4 as reference values.

→ change to:

The correlation between the Iberian Peninsula and the Balkans is generally close to zero in the historical period (below 0.025 in absolute terms on average across all models, and ~~below 0.4~~ within ±0.1 ~~in absolute terms~~ for ~~any~~ nearly all individual models).

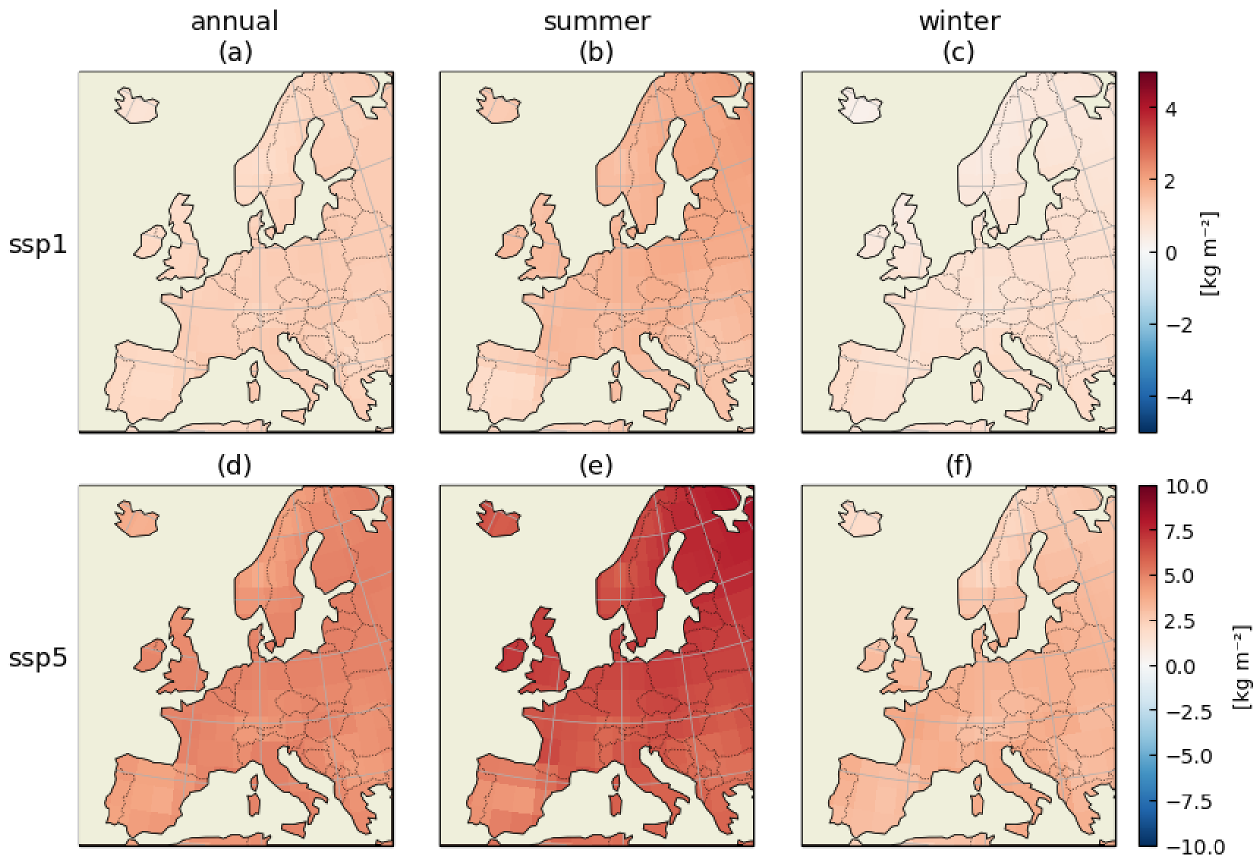
L315: Small correlations indicate that complementarity is possible. However, ideal complementarity is associated with negative correlations. You should further discuss this aspect when commenting on Fig. 6 and 7.

→ insert to L267, see also one previous comment.

Ideally, a negative PV production correlation of exact minus one between two locations would guarantee stable supply of power. A small correlation close to zero would provide stable supply when several different locations are combined. Here, we found that the correlation between the Iberian Peninsula and …

Conclusions: In my understanding, in a context of decreasing aerosol content, the decrease in clear-sky radiation should be associated with increasing water vapour. Am I correct? If so, could you show that?

→ Please see this result of water vapor content vertically integrated through the atmospheric column (prw) for information:



Add interpretation to Sect. 4: In both SSP scenarios, water vapor content (not shown) in the atmosphere increases compared to the present situation, the increase being larger in SSP5 than in SSP1. For SSP1, the observed increase in clear-sky radiation then suggests that the small increase in atmospheric water vapor is negligible as compared to the decrease in aerosol load. All-sky radiation increases even more as cloud cover fraction decreases. In the SSP5 scenario, the observed reduction of clear-sky radiation suggests that the augmented water vapor content has a stronger impact than the decrease in aerosol load. All-sky radiation increases nevertheless, due to a reduction in cloud fraction.

Review 2

General comment:

The manuscript presents an interesting topic that has already been studied using projections from CMIP-5 and also regional climate models. However it is important to estimate projected changes of solar radiation and photovoltaic production with the new generation of climate projections from CMIP-6, in order to know the agreement or disagreement with previous results. I recommend the article for publication, although I have some comments to be addressed first.

→ Thank you for the positive feedback. Please see below our point-to-point responses to your comments.

Specific comments:

Methodology:

It could be good to remark that the PV model is using the inclination of the PV panels. This was not very common in other studies like Jerez et al. 2015.

→ Thanks for bringing this aspect to our attention. We agree that it is worthwhile to mention this methodological aspect. We decided to add the information in L91:

GSEE allows us to simulate PV electricity production of a solar panel on annual to hourly intervals, particularly also accounting for panel orientation (Müller et al., 2019).

Results:

The results on clear sky radiation are very interesting, and show differences between the two scenarios. Although the authors speculate with the reasons behind that differences, the variables that are involved in the explanation are not shown: water vapor content and aerosols. You should include them in the analysis.

→ Please see our response to the last comment from Reviewer 1 for water vapor content.

Is the clear-sky radiation of the different climate models provided by each institute? If not, how it is calculated?

→ Yes, the CMIP6 simulations generally also output clear-sky radiation (Eyring et al. 2016).

In line 170, it would be nice to indicate that the uncertainty in the rsdscs is widespread for the 8.5 scenario.

→ We discussed the uncertainty in the following separate paragraph L190-191.

Regarding the seasonal results: there is an increase of PV production in summer and a decrease in winter months, it should be further commented about this fact in terms of the implications of these changes, considering that PV peaks in summer.

→ Thanks for this comment. We believe that you refer to SSP5 in Fig. 4. We would like to point out that we partly address the implications in the results ("Moreover, the seasonal cycle of PV generation is expected to become more pronounced as the generation grows stronger in summer than in winter (SSP1-2.6) or grows in summer and decreases in winter (SSP5-8.5).", L. 227f) and the discussion section ("Second, we observe a tendency for enhanced seasonal cycles, implying an increased need to buffer such seasonal variability." L. 314f).

We agree that the implications for system design are important and decided to expand the discussion on L316 after "implying an increased need to buffer such seasonal variability. ":

For example, the network planning could consider the combination of seasonally complementary power supply from the PV and wind sources, as reasoned in Sect. 3.3.

Results are based on changes at the end of the century and there is the issue of uncertainty. Can they be useful for policymakers, investors or utilities? A comment on that would enrich the paper.

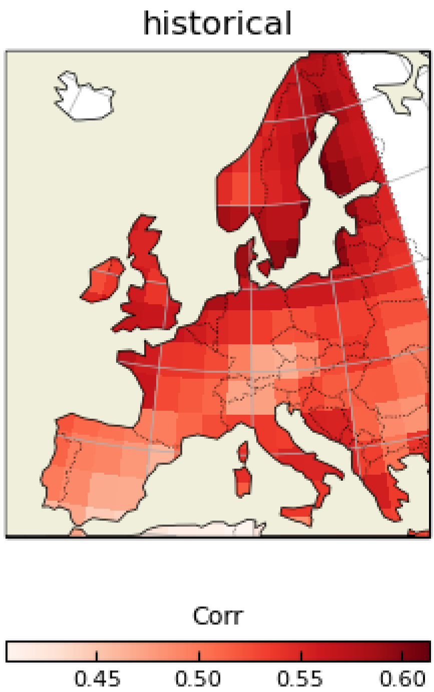
→ Thanks for this comment, which is highly appreciated. We address the issue of uncertainty by comparing agreement on signs of change among dozens of CMIP6 models, furthermore, the analysis of the significance of the correlation is added in the revision. Nevertheless, there are of course remaining uncertainties inherent in climate modeling or any type of projection that covers an entire century. We add the following to make this point clear.

Change to L315:

The changes of correlation coefficients are within 0.42, yet they ought to be taken into account in the future planning of PV production. We acknowledge that real-world energy system design and investment decisions face a range of uncertainties that are related or unrelated to climate. For instance, regulatory frameworks might evolve, innovation could make new technologies available, and financial circumstances can change abruptly in economic crises. Nevertheless, policymakers, investors and utilities need a sound understanding of the climatic boundary conditions for solar photovoltaics in different plausible future climate states.

The PV correlation changes shown are positive for most of the domain, and very low. However, it is not clear how is the correlation in the historical period (Fig 5), it would be good to see them.

→ Fig. 5 is meant to give an overall impression of how correlation changes on a European scale in the future. A more concrete picture is provided by the analysis in Figure 6, which highlights the balancing potential between selected regions and considers seasonal effects. Therefore, we do not want to add more material to the existing Fig. 5 in the manuscript. Nevertheless, we provide a figure as asked for by the reviewer below, for information. The data shown below is not subtracted by annual mean at each averaging step, thus relatively highly correlated. We compute the correlation differences from future scenarios in Fig. 5, the annual cycles are subtracted there. Something noticeable from the historical correlation: while one minimum is located near central Europe (southern Germany, Austria, Switzerland, etc.), these regions also have the maximum increase in PV correlation in SSP5.



In addition, it should be included that a negative correlation close to -1 is the most ideal case, isn't it?

→ insert to L267:

Ideally, negative PV production correlation of exact minus one between two locations would guarantee stable supply of power. A small correlation close to zero would provide stable supply when several different locations are combined. Here, we found that the correlation between the Iberian Peninsula and …

From my point of view, it is not very interesting to analyse the correlation between cells of the domain or regions that include different countries. In terms of energy, countries are operating as single units, if I am not wrong. Correlation between single countries is more appropriate to do this balancing study.

→ Originally, we discussed following the approach in Wohland et al. (2017) by separate countries. However, we have almost one order of magnitude lower spatial resolution using the CMIP6 multi-model composite than EURO-CORDEX they used. Separating countries by interpolation or other methods might introduce unwanted inaccuracy for countries with a smaller area, therefore, we opted to investigate correlations between grid cells for a general pattern instead. More conceptually, we agree that energy decisions are often still taken on a country level, however, there are significant exceptions to that rule. For instance, some countries experience congestion in their transmission grid, and in order to capture this effect, one would want sub-country resolution. Moreover, there are international transmission lines that connect countries, the European Union has policies that affect energy generation and investments do not stop at borders. In order to capture these, one needs a continental scope.

Line 31: Please, add more references to this sentence.

→ referenced added:

Power generation from sunlight is weather dependent and thus fluctuates in space and time (e.g., Bloomfield et al., 2021; van der Wiel et al., 2019; Craig et al, 2019; Ravestein et al., 2018)

- Craig, M. T., Losada Carreño, I., Rossol, M., Hodge, B.-M., and Brancucci, C.: Effects on power system operations of potential changes in wind and solar generation potential under climate change, Environ. Res. Lett., 14, 34014, https://doi.org/10.1088/1748-9326/aaf93b, 2019.
- Ravestein, P., van der Schrier, G., Haarsma, R., Scheele, R., and van den Broek, M.: Vulnerability of European intermittent renewable energy supply to climate change and climate variability, Renewable and Sustainable Energy Reviews, 97, 497–508, https://doi.org/10.1016/j.rser.2018.08.057, 2018.

Line 43: more up to date paper of EURO-CORDEX: "Regional climate downscaling over Europe: perspectives from the EURO-CORDEX community" Jacob et al. 2020. Please state more clear the differences between global and regional climate models.

→ Insert

These assessments were mostly based on data from the Climate Modeling Intercomparison Project Phase 5 (CMIP5, Taylor et al., 2012), where the global climate is simulated with General Circulation Models (GCM); or from the European Coordinated Downscaling Experiment (EURO-CORDEX, Jacob et al., 2020), where GCM output is dynamically downscaled to capture the synoptic atmospheric circulation features of a certain region.

Line 45: not all the models keep the aerosols constant, although most of them. Please correct.

→ However, recent evidence suggests that most EURO-CORDEX models are poorly suited to investigate surface solar radiation because aerosols were kept constant in most of the regional climate models used for the downscaling ().

Line 160: "All-sky radiation evolves differently…" I would say that they evolve similarly: in both scenarios there is an increase, although it is of different magnitude. The other variables evolve differently.

→ All-sky radiation, however, evolves differently also increases in the two scenarios.

Line 297: some other references should be included when it is said "due to a too simple treatment of aerosols…"

***Boé et al. 2020**: Boé, J., Somot, S., Corre, L., & Nabat, P. (2020). Large discrepancies in summer climate change over Europe as projected by global and regional climate models: causes and consequences. Climate Dynamics, 54(5), 2981-3002.*

***Gutiérrez et al. 2020:** Gutiérrez, C., Somot, S., Nabat, P., Mallet, M., Corre, L., van Meijgaard, E., Perpiñán, O. & Gaertner, M. Á. (2020). Future evolution of surface solar radiation and photovoltaic potential in Europe: investigating the role of aerosols. Environmental Research Letters, 15(3), 034035.*

→ Thanks for the suggested references.

insert:

Regional climate models, by contrast, often report a widespread decrease in future all-sky radiation in Europe (e.g. Jerez et al., 2015; Bartok et al., 2017), possibly due to a too simple treatment of aerosols (Bartok et al., 2017; Jerez et al., 2021; Boé et al., 2020; Gutiérrez et al., 2020).

Line 309: "Jerez et al. (2015) also confirmed a slightly positive trend in southern Europe based on regional climate models" I think there is also a difference between the analysed periods.

→ Jerez et al. (2015) also confirmed a slightly positive trend in southern Europe (2070-2099 compared to 1970-1999) based on regional climate models.

In order to help the reader with the results and the comparison, it would be very useful to have the same scale for the maps of the two scenarios.

→ We prefer to not have the same scale of color bars in both SSP scenarios for other variables such as tas or clt in Figs. 1 & 2 and relative change in PV generation in Figs. 3 & 4, because it would make the details within the single SSP with weaker signals less discernible.

Line 319: "In the mitigation SSP1-2.6…" it sounds repetitive with previous sentence, try another formula.

→ In the mitigation SSP1-2.6 scenario, ...

Editor review

Dear editor,

Thank you for your prompt answer to our Author Comments. Regarding your question about the uncertainty of the GSEE simulation, in Sect. 2.2 we newly refer to the concept from Pfenninger and Staffell (2016) describing the model and their use case, where they assessed the uncertainty compared to the observations. While they used meteorological reanalysis and satellite datasets as input, we used climate projections in the study, therefore the performances are not directly comparable. Even though there are no future observations available for validation, we evaluate the difference between future and present, thereby avoiding systematic bias to some extent. Moreover, we now also discuss other uncertainties in modeling future energy systems in the Discussion to underline that the climate-induced uncertainties are just one contributor to overall uncertainties. Nevertheless, the climatic boundary conditions such as changes in solar radiation and PV potentials need to be properly understood in order to guide modeling that takes the other uncertainties with respect to innovation, costs etc. into account.

Yours sincerely,
Xinyuan Hou (on behalf of all authors)