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— ENANDES —



ENANDES+

ENANDES and ENANDES+ Projects

Enhancing Adaptive Capacity of Andean Communities through
Climate Services in Chile, Colombia, Peru (ENANDES), and
Argentina, Bolivia, Ecuador (ENANDES+)

Activity: Co-development of National Renewable Energy Atlases in
South America

Deliverable N°2: Second report (approximately 7 pages), including a summary of the bilateral co-development sessions (~3 pages); Synthesis of feedback and recommendations (~4 pages) based on a structured survey designed to gather users' views on the methodology, code, visualization tools, and other technical aspects.

History of draft preparation and review

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Deliverable 2: Results of the co-development sessions.

WMO ENANDES Project Consultancy: Co-development of National Renewable Energy Atlases in South America – ENANDES and ENANDES+ countries

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Introduction

The WMO High-Resolution National Renewable Energy Atlas for wind, solar, and hydropower initiative (NRA) was launched in 2023 in response to the WMO Members' need for high-resolution information on renewable energy resources in a changing climate. The initiative aims to support countries in advancing towards climate-resilient energy transitions by providing robust, decision-ready information. It addresses the gaps identified in the WMO Energy Survey of 2022, which revealed that many National Meteorological and Hydrological Services (NMHSs) either have outdated national atlases or lack essential climate projection data in their existing atlases.

During its first phase (2024), the initiative was implemented in Chile, Iran, Malawi and Costa Rica, resulting in a comprehensive implementation guideline and open-source codes¹. During its second phase (2025), the methodology was refined to integrate satellite data, in collaboration with the German Weather Service (DWD), and extended to support Tanzania, Cuba, and Croatia received in co-developing their atlases.

Building on the successful outcomes of the first two phases of the WMO Renewables Atlas initiative, the WMO ENANDES and ENANDES+ Projects² supported the third phase of the initiative to address similar existing gaps across the projects' participating countries in South America. This new phase will draw on the technical expertise and data resources of the WMO Regional Climate Prediction Centres where applicable, namely the RCC–Western South America (RCC–WSA) hosted by CIIFEN in Ecuador, and the RCC–Network for Southern South America (RCC–Network–SSA).

The primary goal of the current phase of the initiative under the ENANDES project is to build on previous phases to co-develop national atlases for wind, solar, and hydropower resources in South America. With the goal of empowering NMHSs with the necessary resources to develop and maintain high-resolution national atlases that incorporate current data and future climate projections, the present phase expanded the portfolio of tools developed in the previous ones. Specifically, the general methodology was adapted to the data availability of the pilot countries, and operational optimisations were implemented to ensure a continuous refinement and advancement. Furthermore, the accessibility of the information was enhanced through the development of dedicated factsheets and an interactive webpage.

Summary of the bilateral co-development sessions

As in the previous phases³, the third phase of the WMO NRA initiative embraces a user-centric design approach, following a structured four-step methodology:

¹ <https://energymeteorology.info/reatlas/>

² <https://wmo.int/activities/projects/project-portfolio/enandes-building-regional-adaptive-capacity-and-resilience-climate-variability-and-change-vulnerable>

³ Petitta, M., et al. (2026). From global data to local action: A participatory framework for national wind, solar, and hydropower atlases based on observations, climate projections and artificial intelligence. *Climate Services*, 42, 100663.

- a) A **kick-off meeting** to introduce the context, the goal, and the activities of the project to all the participants (held online on 18/06/2026);
- b) A series of **bilateral meetings** to discuss with each NMHS about engagement of other relevant national institutions to be involved in the co-production process, and exploring the available in-situ observations to be integrated into the NRAs (held online on 07/04/2026 for Perú, on 08/04/2026 for Ecuador, on 15/04/2026 for Chile, on 16/04/2026 for Argentina, and on 30/06/2026 for Bolivia);
- c) A **survey** to be filled in by the participating countries (see Deliverable 1), designed for gathering information about the current activities linked to the generation of NRAs and the available in-situ observations;
- d) A series of **bilateral co-production sessions** to validate the communication material (i.e. the factsheets and the HTML website, presented in Deliverable 3), to present the tailored Jupyter notebooks, and to collect feedback on the first version of the maps.

As steps *a* to *c* have been covered in Deliverable 1, the remainder of this section will focus on the bilateral co-production sessions (step *d*).

Details on the bilateral co-production sessions

The co-production sessions were aimed at both validating the communication material (i.e. the factsheets and the HTML website, presented in Deliverable 3) and presenting the tailored notebooks for capacity building. To this end, we designed the following agenda:

Welcome and introductions [15']
Overview the WMO project [10']
Feedback on factsheet and website [10']
Step by step renewable energy atlases co-production [30' + 10' break + 30']
Step 1: data retrieval
Step 2: data pre-processing
Step 3: downscaling
Step 4: IDW
Step 5: NRA generation
Step 6: visualisation
Step 7: future climate projections
Questions and open discussion [15']

Results of the bilateral co-production sessions

A summary of the bilateral co-production sessions is reported in the following Tables, one for each Country. Each table includes information on the produced atlas, the date of the co-production session, the participants from the NHMSs, and the collected feedback, including whether or not such feedback has been implemented in this phase. For the feedback that have not been directly

addressed, we include a discussion on potential developments for future phases of the WMO NRA project.

Argentina	
Atlas	Solar Atlas
Date	23/06/2026
Participants	• Silvina Righetti (Servicio Meteorológico Nacional de Argentina, SMN) • Fernando Nollas (SMN) • Fiorella Bertone (SMN) • Luciana Stoll (SMN)
Feedback	• It was suggested to depict the anomalies (past climate vs. future climate) as percentage to make comparison among Countries easier → <i>the feedback has been implemented both in the notebooks and in all the communication material (i.e. factsheets and HTML webpage).</i> • It was suggested to add an estimate of uncertainties of the NRAs as this information would be beneficial for decision making → <i>unfortunately this idea is beyond the scope of the present phase of the WMO NRA project, but the suggestion will potentially be taken into consideration for future activities.</i> • The NHMS requested to include Malvinas islands in the visualisation → <i>The request has been addressed, and results are included in the communication material.</i>

Bolivia	
Atlas	Hydropower Atlas
Date	01/07/2026
Participants	• Adrian Wilson Mamani Conde (SENAMHI)
Feedback	• It was recommended to translate the webpage into Spanish → <i>A Spanish version of the HTML webpage has been created.</i>

Chile	
Atlas	Wind Atlas

Date	22/06/2026
Participants	• Juan Crespo (Dirección Meteorológica de Chile, DMC) • Marjorie Alexandra Cataldo Soto (DMC) • Alvaro Costanzo (DMC)
Feedback	• It was suggested to depict the anomalies as percentage → <i>The request has been addressed both in the notebooks and in all the communication material (i.e. factsheets and HTML webpage).</i> • It was suggested to adjust the colormap ranges to better represent the spatial variability of wind speed, and to increase the font sizes to improve readability → <i>The feedback has been implemented both in the notebooks and in all the communication material (i.e. factsheets and HTML webpage).</i> • It was mentioned that the current version of the NRA future climate assessment can quickly get outdated with the upcoming CMIP7 dataset replacing CMIP6 → <i>The protocols of CMIP7 have been released in late 2025⁴, and the dataset is not yet available. For these reasons, this comment is considered valuable for future phases.</i> • The importance of the bilateral co-production session was highlighted as a means to familiarise with the material and tools. This session has been added in the second phase of the WMO NRA initiative, and Chile has already participated in the first phase → <i>This comment is not a request but rather a confirmation that the user-centric design approach used in the WMO NRA project is aligned with the users' expectations and needs.</i>

Ecuador	
Atlas	Hydropower Atlas
Date	17/06/2026
Participants	• Cristina Correo Valdivieso (Instituto Nacional de Meteorología e Hidrología de Ecuador, INAMHI)
Feedback	• It was requested to include the logo of the organisation in the factsheet → <i>The logo has been included in the factsheet during the co-production session, and the feedback has been implemented to all the factsheets of the participating countries.</i> • The approach, methodology, and results were highly recognized.

⁴ Dunne et al. 2025; <https://doi.org/10.5194/gmd-18-6671-2025>

Peru	
Atlas	Solar Atlas
Date	19/06/2026
Participants	• Jose H. Inoue Velarde (Servicio Nacional de Meteorología e Hidrología del Perú, SENAMHI) • Orlando Ccora Tuya (SENAMHI) • Yury Wilson Escajadillo Fernández (SENAMHI) • Grinia Jesus Avalos Roldan (SENAMHI) • Elvis Anthony Medina Dionicio (SENAMHI)
Feedback	• The NHMS noticed that the maps resulting from the WMO NRA were in line with the previous version of NRA on a qualitative level. The participants stated that they plan to carry out a deeper analysis to quantitatively assess the improvements of the current version of NRA with respect to the previous one. → <i>This comment does not need direct action. It has been mentioned here because the results of the analysis performed by SENAMHI would support a quantitative assessment of the quality of the method.</i> • The future climate projections were considered reasonable, as they present an increase in solar energy potential on the Hamazones, where a decrease in precipitation has already been recorded. → <i>As in the previous case, this feedback has been reported as a confirmation of the quality of the outputs of the WMO NRA project.</i> • It was stressed how an estimate of uncertainties and reliability of the NRAs would be beneficial for decision making → <i>Unfortunately this idea is beyond the scope of the present phase of the WMO NRA project, but the suggestion will potentially be taken into consideration for future activities.</i> • Conceptual changes to the methodologies, such as the integration of aerosols and the analysis of diurnal cycle, have been suggested for future phases → <i>Unfortunately this idea is beyond the scope of the present phase of the WMO NRA project, but the suggestion will potentially be taken into consideration for future activities.</i> • It was requested to include a disclaimer in the factsheet stating that the results are not an official publication of the NHMS → <i>The modification has been implemented after the session, validated offline with the Peruvian NHMS, and applied to all the factsheets.</i> • It was requested to add more information to the description of the IPCC scenarios in the HTML webpage. → <i>The request has been addressed and implemented in the HTML webpage.</i>

Analysis of the feedback gathered in a structured survey

Besides the feedback gathered directly during the co-production sessions, we designed a dedicated survey to be completed offline within one week from the co-production session. This section presents the survey and the key results of this systematic feedback collection.

Structured survey

The survey has been shared with the NHMSs as a [Google survey](#) in Spanish to facilitate feedback collection. The questions of the survey are organised in three sections: Methodology, Code and Visualisation tools. The section on visualisation tools entails dedicated questions for the factsheets and the HTML webpage. Figure 1 displays the survey through screenshots.

OMM ENANDES - Atlas de Energía Renovable: Encuesta final

Gracias por participar en el proceso de codesarrollo de los atlas nacionales de energía renovable de la tercera fase de la iniciativa de OMM, en el marco de los proyectos ENANDES y ENANDES+. Apreciaríamos mucho su opinión sobre el método y el material para recopilar comentarios para las siguientes fases.

* Indicates required question

Metodología

¿Es clara la metodología? *

Nada ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 Mucho

¿Es un avance con respecto a lo que se ha utilizado hasta ahora? *

Nada ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 Mucho

¿Tiene algún comentario sobre cómo mejorar la metodología?

Your answer

Código

¿Considera que el código es legible? *

Nada ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 Mucho

¿Está bien documentado el código? *

Nada ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 Mucho

¿Tuvo algún problema al ejecutar el código usted mismo?

Your answer

Herramientas de visualización

¿Le gusta la apariencia de la hoja informativa? *

Nada ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 Mucho

¿Cree que el contenido incluido en la hoja informativa es comprensible e interesante? *

Nada ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 Mucho

¿Cambiaría algo de la hoja informativa?

Your answer

¿Le gusta la apariencia de la página web? *

Nada ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 Mucho

¿Cree que la información proporcionada por el sitio web es comprensible e interesante? *

Nada ☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5 Mucho

¿Cambiaría algo de la página web?

Your answer

¿Algún otro comentario?

Your answer

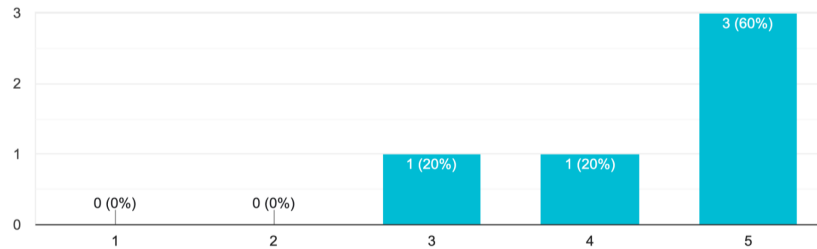
Submit Clear form

Figure 1: Screenshots of the Google survey used for collecting feedbacks.

Results of the survey

We report hereafter the graphs summarising the results of the Likert-scale questions of the survey. The English translation of the answers to the open question are reported in the Appendix.

¿Es clara la metodología?
5 responses



¿Es un avance con respecto a lo que se ha utilizado hasta ahora?
5 responses

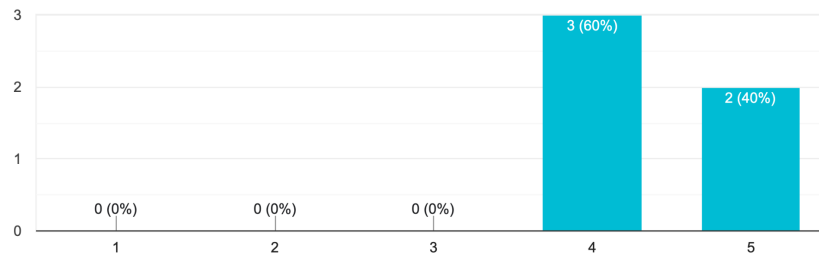
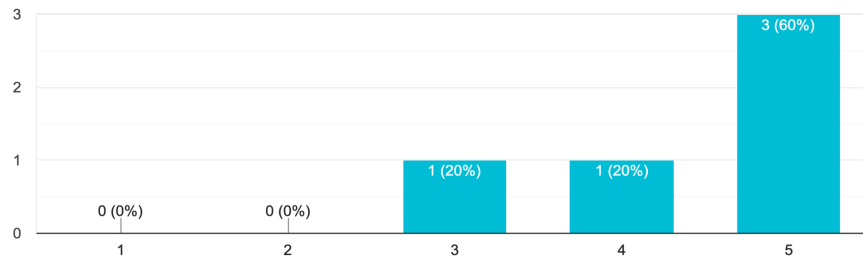


Figure 2: Graphs of the results of the Likert-scale questions of the section “Methodology” of the survey.

¿Considera que el código es legible?
5 responses



¿Está bien documentado el código?
5 responses

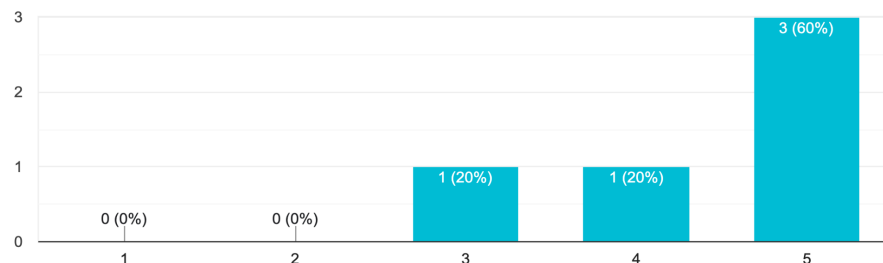
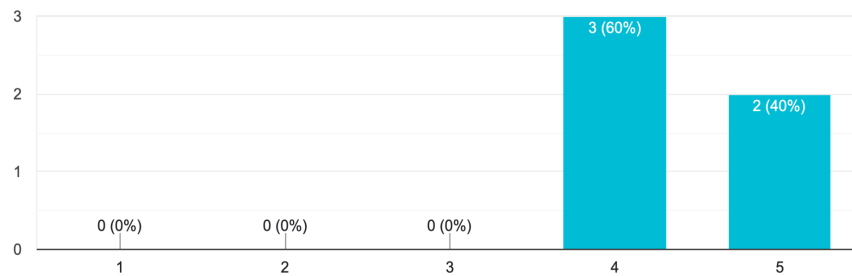


Figure 3: Graphs of the results of the Likert-scale questions of the section “Code” of the survey.

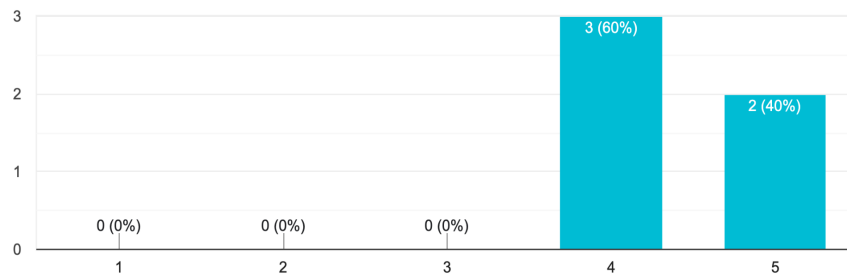
¿Le gusta la apariencia de la hoja informativa?

5 responses



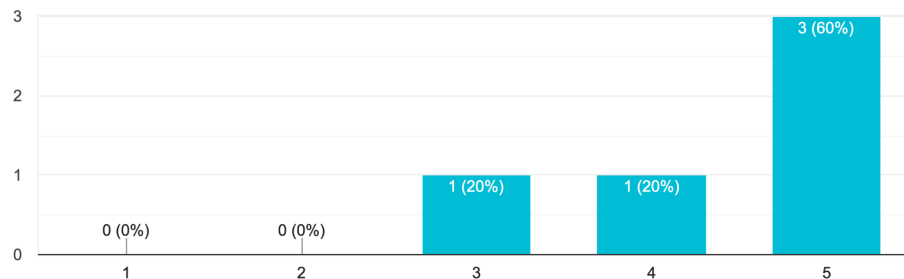
¿Cree que el contenido incluido en la hoja informativa es comprensible e interesante?

5 responses



¿Cree que la información proporcionada por el sitio web es comprensible e interesante?

5 responses



¿Le gusta la apariencia de la página web?

5 responses

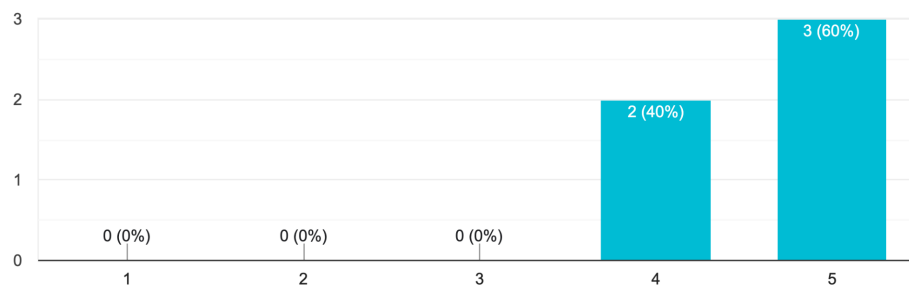


Figure 4: Graphs of the results of the Likert-scale questions of the section “Visualisation tools” of the survey.

An analysis of the results is reported hereafter with comments for each section of the survey. The goal of the analysis is to identify direct actions that need to be carried out within the third phase

of the WMO NRA project as well as feedback that will lay the foundation for future improvements in the next phases.

Methodology

The methodology has received positive reviews. In particular, it received the maximum score, i.e. 5 out of 5, for its clarity (Fig. 2). The lowest score was 3 out of 5 and is linked to the comment of the Peruvian NHMS which suggested to include aerosols and diurnal cycle in the method. This idea is beyond the scope of the present phase of the WMO NRA project. Although it could be considered for future improvements, careful considerations are needed. Including information on aerosol in the downscaling might complicate the application of the methodology to future climate conditions. Moreover, expanding the analysis to the diurnal cycle would tremendously enhance the computational resources needed as the method is currently applied to monthly averages.

The participating countries gave a score of 4 out of 5 in response to the question about the potential improvement with respect to existing atlases (Fig. 2). The answers to the open questions and personal communications clarified that many of the countries consider this question to be premature. A concrete answer would need to be based on detailed quantitative analyses. The results of such an analysis would be essential for future phases of the project. Therefore, it is suggested to closely collaborate with the participating countries to harness such a key knowledge.

Code

The answers to the questions related to the code are quite positive, with an average score of 5 out of 5 for both the readability and the documentation (Fig. 3). However, it emerged from the open questions that the NHMSs were still in the process of testing the code. It might be useful to repeat the survey in a later stage, when the participating countries have had the time to consolidate their understanding and use of the provided material. It is worth mentioning that DMC (Chile) that also participated during the first phase of the project in 2024, provided feedback on the use of the results of the 2024 phase through a written interview (results used for the policy brief included in Deliverable 3). The feedback was quite positive. DMC has operationalised the method, and the information is being used by the Ministry of Energy for long-term planning. This insight is key to ensure that, with time, the method is usable and useful to support decision making towards a resilient transition.

Visualisation tools

The visualisation tools include the Country factsheets and the HTML website. The country factsheets received an average score of 4 out of 5 for both the layout and the content. Specific modifications have been requested by the countries in the open question, such as:

- Factsheet of Chile: the NHMS required to change the logo of the organisation → *the feedback has been implemented in both the Spanish and English version of the factsheets.*
- All factsheets: an outdated version of the data used for the solar atlas was included → *the text has been modified in both the Spanish and English version to describe CERES dataset instead of SARAH-3.*

- Factsheet of Peru: the NHMS requested to modify the text describing the used in-situ observations → *the text has been amended in both Spanish and English versions of the factsheet.*
- Factsheet of Argentina: the NHMS asked to change the logo of the organisation → *the logo has been updated.*
- Factsheet of Argentina: the country requested to include the Malvinas island in the map → *the used shapefile has been modified and the maps have been updated in all visualisation tools.*
- All factsheet: the Argentinian NHMS stated that the wording “Responsible partner” to indicate the institute participating the project was not clear → *the wording has been modified as “User and collaborator” in both the Spanish and English version of all factsheets.*

The HTML website received an average score of 5 out of 5 for both the layout and the content. Specific requests have been detailed in the open questions and are reported hereafter:

- Forsee an option to download the maps → *the request has been addressed, and the HTML website has been modified respectively;*
- Create a Spanish version HTML webpage → *An Spanish version of the HTML webpage has been created.*

NMS Argentina suggested to visualize all the available atlases in the region through a continental map. This is indeed an interesting idea for future phases of the project, as, to be visually effective, all NRAs for the majority of countries would be necessary.

Recommendations for future activities

Based on the feedback received during the co-production sessions and in the survey, we draw the following recommendation for future activities. The recommendations are reported in a table including three main areas of considerations, i.e. the utilised user-centric design approach, the visualisation tools developed in the third phase of the project including both the country factsheets and the HTML webpage, and the methodological framework developed in the previous phases of the project and further improved for South America within this phase.

<u>User-centric design approach</u>	
<i>Recommendation</i>	Include a bilateral co-production session for each country: a bilateral co-production session should be preferred to a general workshop addressing the needs of multiple countries. This one-on-one meeting is an opportunity to promptly solve problems and speed up the operationalisation of the NRA method.

<i>Potential difficulties</i>	-
<u>Visualisation tools</u>	
<i>Recommendation</i>	Design the communication material in the local language: the visualisation tools, i.e. the country factsheet and the HTML webpage, prepared during the current phase of the WMO NRA project, proved to be useful to provide ready-to-use material for a wider public than the NHMSs. However, to ensure effective communication, such a material needs to be available in the local language(s).
<i>Potential difficulties</i>	-
<u>Methodological framework</u>	
<i>Recommendation 1</i>	Implementation of an uncertainty assessment method: in line with Deliverable 1, the countries requested an assessment of the uncertainties and reliability of the NRA. In particular, the users were interested in an estimate of the uncertainties of the downscaled meteorological variables.
<i>Potential difficulties</i>	The main obstacle to effectively perform such an analysis is the difficulties in identifying authoritative and independent data sources to be used as a benchmark. The in-situ observations of the national network of meteorological stations cannot be considered as they are assimilated in the NRA. Therefore, other data sources need to be identified to this end.
<i>Recommendation 2</i>	Assess the uncertainties of future climate projections: as suggested in Deliverable 1, the uncertainty analysis should be extended to the future climate projections. Generally, the uncertainty of climate projections is assessed as the variability of a model ensemble. At the time being, only one model is used for the development of NRAs.
<i>Potential difficulties</i>	Only one model of the CMIP6 project provides projections of river discharge. This would limit the application of the uncertainty estimate for climate projections to solar and wind resources alone. Another key aspect to consider is the time and IT resources needed to calculate the NRA for future climate, as they are proportional to the number of CMIP models included in the analysis. Lastly, the concept of future

	climate uncertainty is not straightforward, and might complicate even further the interpretation of the information by decision-makers.
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Appendix – Responses to the open questions of the survey

Do you have any comments on how to improve the methodology?

- INAMHI is beginning to develop an atlas, which is why it is essential to use this methodology.
- Regarding the methodology used for Peru, it is unclear whether the effects of aerosols, water vapor, and solar cycles were taken into account when estimating solar radiation.
- A priori, the methodology seemed clear to us, but we believe that we should evaluate the results and the uncertainties of its application.

Did you have any problems running the code yourself?

- Not yet.
- We are still running.
- There were issues creating the environments from the YML files, so the packages had to be installed manually in order to use them. Additionally, for processing the observed data from Peru, script 4.1. specifies input files that we have been unable to find on the shared GitHub repository, such as: "stations_info.xlsx", "stations_coordinates_decimal.csv", and "resumen_estaciones_peru.xlsx". If possible, it would be very helpful if you could send it to us, as we are unfamiliar with its structure and therefore unable to generate these files ourselves.
- The truth is, we haven't been able to look at the scripts and documentation in detail yet. That is the only reason we rated it a 4. What we saw in the Workshop seemed good to us.

Would you change anything in the fact sheet?

- Yes, in the case of Chile, I would say that the responsible entity is the Chilean Meteorological Service (DMC), which is under the General Directorate of Civil Aviation (DGAC).
- The content has been reviewed, and within the Earth Observations section, it has been determined that the SARAH-3 satellite does not fully cover the northern part of Peru. Additionally, the code was found to use another satellite called CERES. Furthermore, regarding the station data, it is proposed that the following be included: "For this project, SENAMHI has considered using data from 197 stations, 15 of which include horizontal global irradiance, covering the period 1975–1990." Finally, since the resulting product pertains to renewable solar energy, it is proposed that the wording be oriented toward that

topic; therefore, the reference to hydroelectric atlases in this fact sheet may be omitted. Attached to this reply email is the document with the highlighted content for your review.

- The SMN logo needs to be changed, and the Malvinas Islands must be incorporated into the maps shown. The word 'Objetivos' is misspelled. Regarding the satellite irradiance data, was SARA-3 or CERES used? In the Results section, it states that the responsible entity is the SMN, but the disclaimer below states that the results are not the responsibility of the SMN. It is not entirely clear to us what we would be responsible for.

Would you change anything in the HTML webpage?

- No.
- Please include a button to download the maps on display. Furthermore, when selecting the projection year, please consider using a higher resolution.
- We would like the webpage to be in Spanish, to be interoperable for navigating the images (for example, to be able to zoom), and to have the option to download the maps. We also think it would be good to have a map with the information for all countries together.

Any other comments?

- We would be grateful if you could share the link to the website so that we can examine it in greater detail. We would also appreciate it if you could provide us with further details regarding the implementation of the methodology. Finally, we would ask you to send us the resulting tabulated data on a monthly and annual basis so that we can analyse it.