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°3: Final report (approximately 15 pages), including an overall summary of the project (~5 pages); Finalized country factsheets on data analysis and produced maps for each country; Interactive HTML webpage displaying the visualized results of the developed atlases; Draft conference paper on the methodology and results (~5 pages); and a policy brief document as outlined in task 6 (~5 pages). The report should also include the formal transfer of all collected data and associated intellectual property (IP) to WMO.

History of draft preparation and review

V1.0- Initial draft by Sara Dal Gesso and Alessandro Moser	03/07/2026
V2.0 Reviewed by Hamid Bastani	08/07/2026

Deliverable 3: Final report

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

Table of Contents

Introduction

The High-Resolution National Renewable Energy Atlas for wind, solar, and hydropower initiative (NRA) is a pioneering initiative launched by the World Meteorological Organization (WMO) in response to the Members ‘need for high-quality, high-resolution data on renewable energy resources in a changing climate. The initiative aims to support countries in advancing towards climate-resilient energy transitions by providing robust and 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Energy Survey of 2022, which revealed that many National Meteorological and Hydrological Services (NMHSs) either have outdated national atlases or lack essential climate projection data in their existing atlases.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 codes[1]. 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 Project[2] decided to take this unique opportunity to address similar existing gaps across the participating countries in South America. This new phase drew on the technical expertise and data resources of the WMO Regional Climate Prediction, namely the RCC–Western South America (RCC–WSA) hosted by CIIFEN in Ecuador, and the RCC–Network for Southern South America (RCC–Network–SSA). In particular, the IRI Data Library from RCC-WSA has been integrated in the wind-energy atlas, expanding the wealth of open-source data the methodology is built upon.

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 participating countries of the ENANDES and ENANDES+ projects 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 phases in 2024 and 2025[3]. Specifically, the general methodology was adapted to the data availability of the participating pilot countries. Furthermore, the accessibility of the information was enhanced through the development of dedicated factsheets and an interactive HMTL webpage for communication means.

Summary of the project

The third phase of the WMO NRA initiative, supported by the ENANDES and ENANDES+ projects, has a geographical focus on Latin America. In particular, the selected pilot Countries are

[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] https://energymeteorology.info/reatlas/

the following: Argentina, Bolivia, Chile, Ecuador and Peru. Through the established co-development process defined in the previous phases and discussed in Deliverable 2, the current project achieved the following milestones:

1. Implementation of operational optimisations of the methodology (see the section below for further information) to ensure continuous advancements and capitalise on the available data in the region;
2. Development of five NRAs to support resilient transition throughout the continent;
3. Design of a communication package to enhance impact and outreach of the results through a user-friendly HTML webpage and a set of factsheets.

Due to limitations in the available resources at the NHMSs of the pilot Countries, we were requested to support the development of five NRAs instead of seven. The corresponding effort of two NRAs has been devoted to:

- Implementing additional operational improvements of the methodology with respect to the ones envisioned in Deliverable 1(see next section for details);
- Integrating a tailored data cleaning for station data in the Jupyter Notebooks shared with each country;
- Designing a "master notebook" for policy makers to illustrate the methodology step-by-step and provide a simplified access to the python workflow and the figures.

In the following, we explain the main advancements of the methodology and the concrete outputs of the activities.

Operational optimisations of the methodology

The Deliverable 1 presented a list of suggested improvements under three main directions: Operational optimization, Methodology enrichment, and long-term advancements. The proposed improvements under operational optimizations have been implemented in the current phase of the project, while the other two groups of improvements could be considered in future phases of the WMO NRA initiative. A detailed description of the operational optimisations implemented follows. It is worth mentioning that the operational optimisation named "*Enhance hydrological data assimilation*" was not envisioned during the analysis performed in Deliverable 1, and it has been included during the NRAs generation. We highlighted this latter improvement by making the title row in yellow.

Optimisation of river discharge clipping	
Methodological modification:	Interpolation of CMIP6 projections onto the GloFAS grid and application of the river mask prior to the delta computation. Extension of the clipping procedure to improve dataset extraction within national boundary geometries and reduce missing values at borders.

Jupyter notebook upgrades:	*ATLAS_hydro_scenarios.ipynb:* Modify *clip()* function with additional parameters for more accurate extraction of datasets within national boundaries. Addition of interpolation function with nearest neighbour method to bring CMIP6 data onto the GloFAS grid, followed by a clipping function applied to both datasets using the river shapefile.
Modification of delta calculation for hydropower atlases	
Methodological modification:	Anomalies between SSP scenarios and the historical experiment are computed as monthly percentages differences relative to the historical baseline. Future river discharge is then aggregated by averaging over sub-basins at different spatial resolution levels.
Jupyter notebook upgrades:	*ATLAS_hydro_scenarios.ipynb:* Application of the percentage in the delta function. Conversion of the percentage when future river discharge is calculated from the reanalysis data set. Subbasin statistics also for the future climate and saving the results as GeoJSON files. *ATLAS_hydro_plots_scenarios.ipynb:* Maps of the discharge delta and projected future river discharge following the catchment geometries at the two spatial resolutions considered.
Data blending of ERA5 and ERA5Land datasets	
Methodological modification:	Combination of ERA5-Land over terrestrial areas with ERA5 data along coastal grid cells. ERA5 is first interpolated onto the ERA5-Land grid, and then used to replace missing coastal values.
Jupyter notebook upgrades:	*ATLAS_preprocessing.ipynb:* Interpolation of ERA5 to the ERA5-Land spatial grid using bilinear interpolation. ERA5-Land values are retained over land areas, while ERA5 data are used for coastal grid cells to fill missing values. The merged dataset is then clipped to the national boundary geometry using parameters that improve accuracy near borders.
Integration of a simplified data cleaning	
Methodological modification:	Integration of a simplified version of data cleaning for a first evaluation of station data. The data cleaning includes harmonization of station metadata and variable names, standardization of date and time formats, handling of missing and duplicated records, filtering of invalid or inconsistent values, detection of basic outliers and quality issues, and restructuring of datasets into a common format.
Jupyter notebook upgrades:	*ATLAS_stations_data_{country}_preprocessing.ipynb:* dedicated notebook developed for country specific station preprocessing. It deals with heterogeneous data structures, object types, storage formats, and sharing mechanisms across countries, ensuring harmonized input datasets for subsequent analysis.

Enhance hydrological data assimilation	
Methodological modification:	Improvement of the method for assimilating hydrological data in the NRA. A weighted mean is applied between the GloFAS data aggregated over the sub-basin level 12 geometry and the in-situ observations provided by the countries. The weights are based on best practices in data assimilation, and are meant to be optimised by the NHMSs as the most knowledgeable entity to optimise the method. The observations are automatically assimilated at sub-basin level 5 through the aggregation.
Jupyter notebook upgrades:	*ATLAS_hydro_station_integration_and_plots_present:* When station data are available, each gauging station is assigned a weight. The integration function compares the station and basin GeoDataFrames, identifies the corresponding HydroBASINS polygons, and updates the basin river discharge using a weighted average. Basins containing multiple stations are processed by combining all station contributions before applying the correction.

Besides the above-mentioned operational optimisations, we identified and implemented the most suitable data sources for the region. The following table presents the new data sources integrated in the present phase.

Atlas	**Source**	**Variable**	**Use**	**RCC**
Solar	CERES	Global Horizontal Irradiance (GHI)	Substituting SARAH dataset, not available in the area.	-
Wind	IRI Data Library	Monthly climatology of 10 m wind components (u,v)	Additional dataset.	RCC-OSA

Outputs of the project

As a result of the carried-out activities, the third phase of the WMO NRA initiative developed:

A. Five NRAs: two solar NRAs (Argentina and Perú), two hydropower NRAs (Bolivia and Ecuador), and one wind NRA (Chile);
B. The updated version of the Jupyter Notebooks available through GitHub.
C. A communication package including:
    a. An HTML webpage that will be integrated into the CIIFEN ENANDES website (https://crc-osa.ciifen.org/en/CST/);
    b. A set of Country factsheets;
D. The draft of a conference paper;
E. A policy brief;

F. A Master notebook for policy makers: a Jupyter notebook with a simplified workflow available on GitHub, and the corresponding video uploaded in the WMO SharePoint (Appendix).

Country factsheets

The communication package includes a set of factsheets tailored for each Country. All the factsheets have been structured according to the approved template presented in Deliverable 1, and designed in line with WMO designing colour codes. The content of the factsheets has been approved by the participating countries during the bilaterial co-production sessions, ensuring alignment with the users' expectations (see Deliverable 2 for more information on the bilaterial co-production sessions). The final products, in both English and Spanish, are accessible through the WMO Project's shared folder. We report hereafter the English version of the documents.

National Renewable-energy Atlases for South America – ARGENTINA

WORLD METEOROLOGICAL ORGANIZATION

The National Renewable-energy Atlas (NRA) initiative is a pioneering project launched by the World Meteorological Organization (WMO) in response to the urgent need of National Meteorological and Hydrological Services (NMHSs) for high-quality, high-resolution data on renewable energy resources in a changing climate, essential for climate-resilient energy transition. The WMO ENANDES+ Project provided the enabling context and opportunity to focus on South America with the primary goal of co-developing national atlases for wind, solar and hydropower resources, and empowering NMHSs with the necessary resources to develop and maintain high-resolution national atlases that incorporate current data and future climate projections.

Method:

The technical framework, fully described in the WMO technical guidelines, consists of a Machine-Learning based method of downscaling and data blending, based on reliable and accessible data sources. The results compare historical data – combining reanalyses, earth observations and possibly station data – with climate projections of two shared socioeconomic pathways (SSPs), specifically SSP3-7.0 and SSP5-8.5, from a single CMIP6 model.

Data:

The foundation of the NRA framework is built on reliable and accessible data sources. Specifically, the data sources are as follows.

- **Re-analyses**: ERA5-Land is a reanalysis dataset providing hourly data for land variables at 9 km resolution. Along the coast, such a dataset is blended with its lower-resolution (25 km), global counterpart, ERA5. For hydropower atlases, the method employes GloFAS, a gridded modelled daily hydrological time series forced with meteorological reanalysis data.
- **Earth Observations**: GLO-90 is the Copernicus Digital Surface Model (DSM) that represents the surface of the Earth at 90 m resolution. For solar irradiance, the method exploits CERES, a NASA-led climate data collection spanning from 2000 to present.
- **Climate projections**: CMIP6 provides daily and monthly global climate projections computed in the framework of the 6th phase of the Coupled Model Intercomparison Project.

OUTCOMES

User and collaborator:

Servicio Meteorológico Nacional Argentina — Argentinian Meteorological Institute – SMN

Objectives:

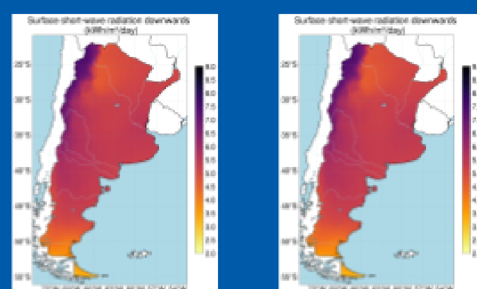
- Update the current solar energy atlas finalised in 2007;
- Integrate climate scenarios to assess climate change impact on renewable resources.

Station data:

The Argentinian NHMS manages 110 stations throughout the Country, among which 10 include Global Horizontal Irradiance (GHI) over the period 2013-2026.

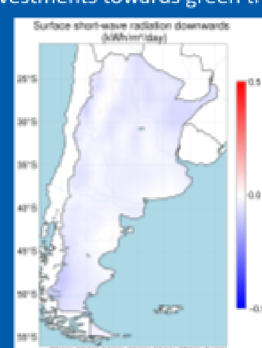
Renewable energy atlases:

2025 2050



Renewable energy opportunities:

A general decrease in solar energy potential is foreseen for the upcoming decades. This forecast is key for climate-smart investments towards green transition.



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Disclaimer: Results presented herein are outputs of the ENANDES / ENANDES+ co-development NRA activities (2026). They are not an official publication of the WMO nor of the National Hydrometeorological Service of Argentina.

National Renewable-energy Atlases for South America – BOLIVIA

The National Renewable-energy Atlas (NRA) initiative is a pioneering project launched by the World Meteorological Organization (WMO) in response to the urgent need of National Meteorological and Hydrological Services (NMHSs) for high-quality, high-resolution data on renewable energy resources in a changing climate, essential for climate-resilient energy transition. The WMO ENANDES+ Project provided the enabling context and opportunity to focus on South America with the primary goal of co-developing national atlases for wind, solar and hydropower resources, and empowering NMHSs with the necessary resources to develop and maintain high-resolution national atlases that incorporate current data and future climate projections.

Method:

The technical framework, fully described in the WMO technical guidelines, consists of a Machine-Learning based method of downscaling and data blending, based on reliable and accessible data sources. The results compare historical data – combining reanalyses, earth observations and possibly station data – with climate projections of two shared socioeconomic pathways (SSPs), specifically SSP3-7.0 and SSP5-8.5, from a single CMIP6 model.

Data:

The foundation of the NRA framework is built on reliable and accessible data sources. Specifically, the data sources are as follows.

- **Re-analyses**: ERA5-Land is a reanalysis dataset providing hourly data for land variables at 9 km resolution. Along the coast, such a dataset is blended with its lower-resolution (25 km), global counterpart, ERA5. For hydropower atlases, the method employes GloFAS, a gridded modelled daily hydrological time series forced with meteorological reanalysis data.
- **Earth Observations**: GLO-90 is the Copernicus Digital Surface Model (DSM) that represents the surface of the Earth at 90 m resolution. For solar irradiance, the method exploits CERES, a NASA-led climate data collection spanning from 2000 to present.
- **Climate projections**: CMIP6 provides daily and monthly global climate projections computed in the framework of the 6th phase of the Coupled Model Intercomparison Project.

OUTCOMES

User and collaborator:

Bolivian Hydro-Meteorological Institute – SENAMHI

Objectives:

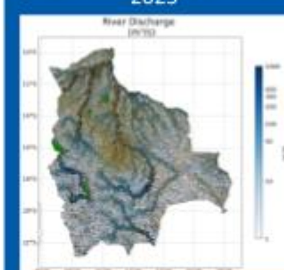
- Assessing the renewable energy potential to accelerate transition;
- Integration of climate scenarios to assess climate change impact on renewable resources.

Station data:

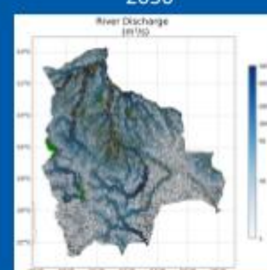
The Bolivian NHMS manages 40 stations measuring water level and 5 river discharge. However, the present results do not integrate station data.

Renewable energy atlases:

2025

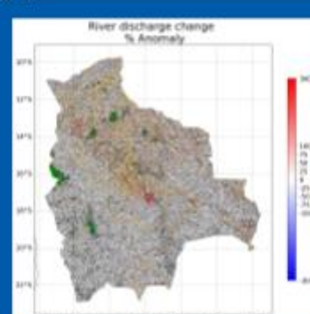


2050



Renewable energy opportunities:

The hydropower potential is forecasted to either increase or decrease depending on the considered basin. This information is key for climate-smart investments towards green transition.



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National Renewable-energy Atlases for South America – CHILE

WORLD METEOROLOGICAL ORGANIZATION

The National Renewable-energy Atlas (NRA) initiative is a pioneering project launched by the World Meteorological Organization (WMO) in response to the urgent need of National Meteorological and Hydrological Services (NMHSs) for high-quality, high-resolution data on renewable energy resources in a changing climate, essential for climate-resilient energy transition. The WMO ENANDES+ Project provided the enabling context and opportunity to focus on South America with the primary goal of co-developing national atlases for wind, solar and hydropower resources, and empowering NMHSs with the necessary resources to develop and maintain high-resolution national atlases that incorporate current data and future climate projections.

Method:

The technical framework, fully described in the WMO technical guidelines, consists of a Machine-Learning based method of downscaling and data blending, based on reliable and accessible data sources. The results compare historical data – combining reanalyses, earth observations and possibly station data – with climate projections of two shared socioeconomic pathways (SSPs), specifically SSP3-7.0 and SSP5-8.5, from a single CMIP6 model.

Data:

The foundation of the NRA framework is built on reliable and accessible data sources. Specifically, the data sources are as follows.

- **Re-analyses**: ERA5-Land is a reanalysis dataset providing hourly data for land variables at 9 km resolution. Along the coast, such a dataset is blended with its lower-resolution (25 km), global counterpart, ERA5. For hydropower atlases, the method employes GloFAS, a gridded modelled daily hydrological time series forced with meteorological reanalysis data.
- **Earth Observations**: GLO-90 is the Copernicus Digital Surface Model (DSM) that represents the surface of the Earth at 90 m resolution. For solar irradiance, the method exploits CERES, a NASA-led climate data collection spanning from 2000 to present.
- **Climate projections**: CMIP6 provides daily and monthly global climate projections computed in the framework of the 6th phase of the Coupled Model Intercomparison Project.

OUTCOMES

User and collaborator:

Chilean Meteorological Service – DMC

Objectives:

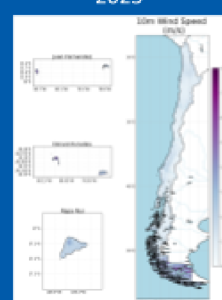
- Generation of a wind-energy atlas, currently not available for strategic decisions;
- Future climate projections are a key element.

Station data:

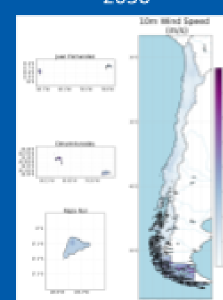
The Chilean NHMS operates a national network of 100 meteorological stations equipped with anemometers that measure wind speed and direction at 10 m.

Renewable energy atlases:

2025

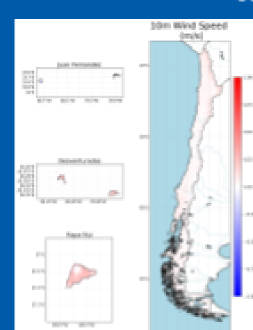


2050



Renewable energy opportunities:

The overall Country presents an increase in wind energy potential, especially in the southern regions, providing emerging opportunities of renewable energy production.



ADAPTATION FUND — ENANDES — ENANDES+ Schweizerische Eidgenossenschaft Confédération suisse Confederazione Svizzera Confederaziun svizra

National Renewable-energy Atlases for South America – ECUADOR

WORLD METEOROLOGICAL ORGANIZATION

The National Renewable-energy Atlas (NRA) initiative is a pioneering project launched by the World Meteorological Organization (WMO) in response to the urgent need of National Meteorological and Hydrological Services (NMHSs) for high-quality, high-resolution data on renewable energy resources in a changing climate, essential for climate-resilient energy transition. The WMO ENANDES+ Project provided the enabling context and opportunity to focus on South America with the primary goal of co-developing national atlases for wind, solar and hydropower resources, and empowering NMHSs with the necessary resources to develop and maintain high-resolution national atlases that incorporate current data and future climate projections.

Method:

The technical framework, fully described in the WMO technical guidelines, consists of a Machine-Learning based method of downscaling and data blending, based on reliable and accessible data sources. The results compare historical data – combining reanalyses, earth observations and possibly station data – with climate projections of two shared socioeconomic pathways (SSPs), specifically SSP3-7.0 and SSP5-8.5, from a single CMIP6 model.

Data:

The foundation of the NRA framework is built on reliable and accessible data sources. Specifically, the data sources are as follows.

- **Re-analyses**: ERA5-Land is a reanalysis dataset providing hourly data for land variables at 9 km resolution. Along the coast, such a dataset is blended with its lower-resolution (25 km), global counterpart, ERA5. For hydropower atlases, the method employs GloFAS, a gridded modelled daily hydrological time series forced with meteorological reanalysis data.
- **Earth Observations**: GLO-90 is the Copernicus Digital Surface Model (DSM) that represents the surface of the Earth at 90 m resolution. For solar irradiance, the method exploits CERES, a NASA-led climate data collection spanning from 2000 to present.
- **Climate projections**: CMIP6 provides daily and monthly global climate projections computed in the framework of the 6th phase of the Coupled Model Intercomparison Project.

OUTCOMES

User and collaborator:

Ecuadorian Meteorological Institute – INAMHI

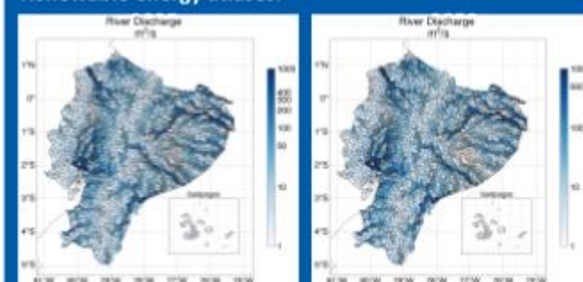
Objectives:

- Expanding the Hydropower NRA, which mainly focused on the infrastructure, with climate information;
- Incorporating climate projections for long-term planning.

Station data:

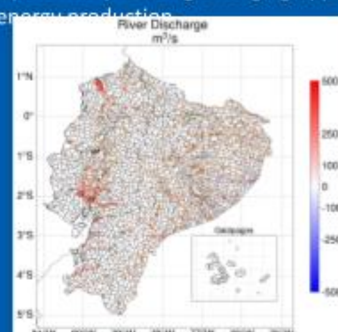
The Ecuadorian Meteorological Institute has a set of 20 stations measuring Precipitation, Surface Water Runoff, and River discharge from 1985 to 2015.

Renewable energy atlases:



Renewable energy opportunities:

The western part of the Country presents an increase in hydropower potential providing emerging opportunities of renewable energy production.



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National Renewable-energy Atlases for South America – PERU

The National Renewable-energy Atlas (NRA) initiative is a pioneering project launched by the World Meteorological Organization (WMO) in response to the urgent need of National Meteorological and Hydrological Services (NMHSs) for high-quality, high-resolution data on renewable energy resources in a changing climate, essential for climate-resilient energy transition. The WMO ENANDES+ Project provided the enabling context and opportunity to focus on South America with the primary goal of co-developing national atlases for wind, solar and hydropower resources, and empowering NMHSs with the necessary resources to develop and maintain high-resolution national atlases that incorporate current data and future climate projections.

Method:

The technical framework, fully described in the WMO technical guidelines, consists of a Machine-Learning based method of downscaling and data blending, based on reliable and accessible data sources. The results compare historical data – combining reanalyses, earth observations and possibly station data – with climate projections of two shared socioeconomic pathways (SSPs), specifically SSP3-7.0 and SSP5-8.5, from a single CMIP6 model.

Data:

The foundation of the NRA framework is built on reliable and accessible data sources. Specifically, the data sources are as follows.

- **Re-analyses**: ERA5-Land is a reanalysis dataset providing hourly data for land variables at 9 km resolution. Along the coast, such a dataset is blended with its lower-resolution (25 km), global counterpart, ERA5. For hydropower atlases, the method employes GloFAS, a gridded modelled daily hydrological time series forced with meteorological reanalysis data.
- **Earth Observations**: GLO-90 is the Copernicus Digital Surface Model (DSM) that represents the surface of the Earth at 90 m resolution. For solar irradiance, the method exploits CERES, a NASA-led climate data collection spanning from 2000 to present.
- **Climate projections**: CMIP6 provides daily and monthly global climate projections computed in the framework of the 6th phase of the Coupled Model Intercomparison Project.

OUTCOMES

User and collaborator:

Peruvian Meteorological Institute – SENAMHI

Objectives:

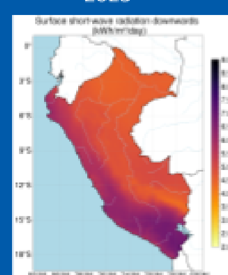
- Updating the current Solar NRA, created in 2003;
- Expanding the utilised data with open-source data such as reanalyses;
- Integrating climate scenarios for long-term planning.

Station data:

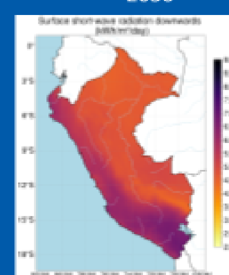
For this project, SENAMHI has drawn on data from 197 stations, 15 of which include global horizontal irradiance over the period 1975–1990.

Renewable energy atlases:

2025

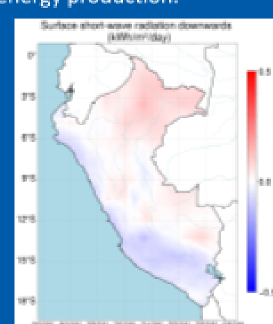


2050



Renewable energy opportunities:

The eastern part of the Country presents a net increase in solar energy potential, providing emerging opportunities of renewable energy production.



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Disclaimer: Results presented herein are outputs of the ENANDES / ENANDES+ co-development NRA activities (2026). They are not an official publication of the WMO nor of the National Hydrometeorological Service of Perù.

Interactive HTML webpage

In addition to the country factsheets, the communication package includes an HTML webpage, which will be integrated into the CIIFEN ENANDES CST[4]. It could also be integrated into the WMO energy and meteorology portal[5]. The introduction part of the webpage includes a description of the objective of the current phase of the WMO NRA initiative under the WMO ENANDES project. The user is able to select the country and the NRA of interest through two independent drop-down menus. This first combination of choices visualises the corresponding atlases. At this point, the user can select the reference year in the future, either 2050 or 2100, and a socio-economic pathway (SSP) as defined by the IPCC. It is then possible to visualise the corresponding map for future-day climate and compare the two NRAs through the anomaly. Screenshots of the HTML webpage are reported hereafter.

A screenshot of the HTML webpage is shown for reference.

Figure 1: Screenshot of the HTML webpage: introductory banner.

[4] https://crc-osa.ciifen.org/en/cst-enandes/
[5] https://energymeteorology.info/reatlas/

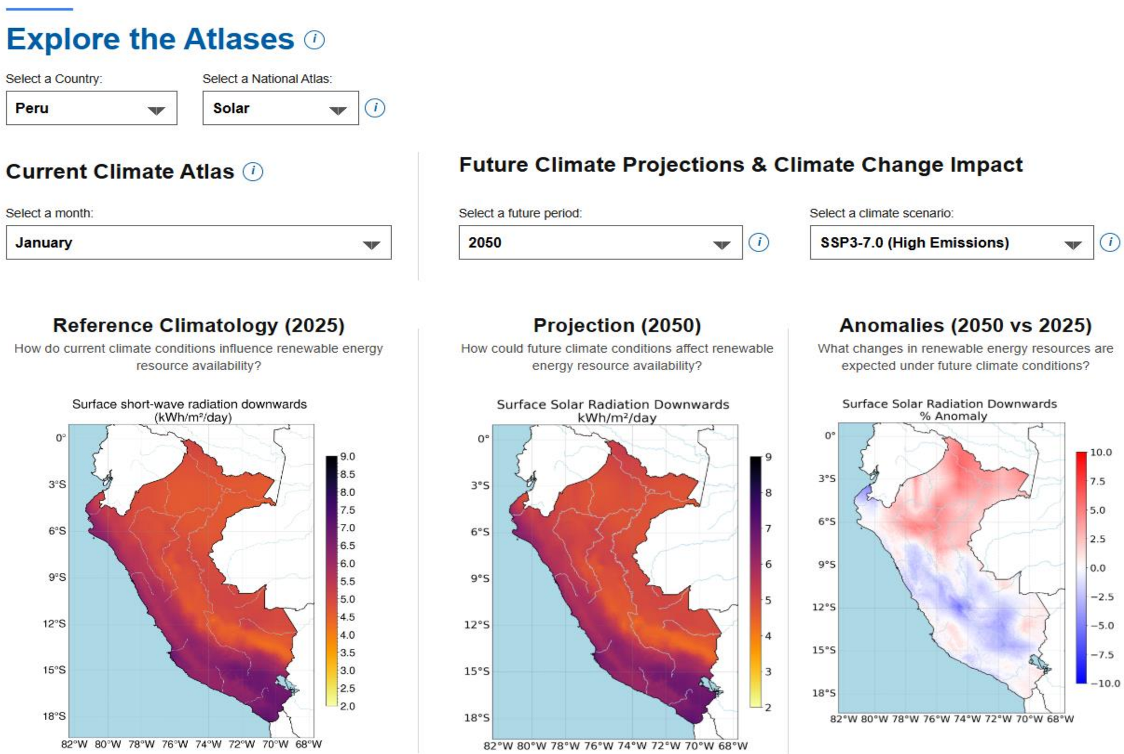


Figure 2: Screenshot of the HTML webpage: visualisation of the NRA maps.

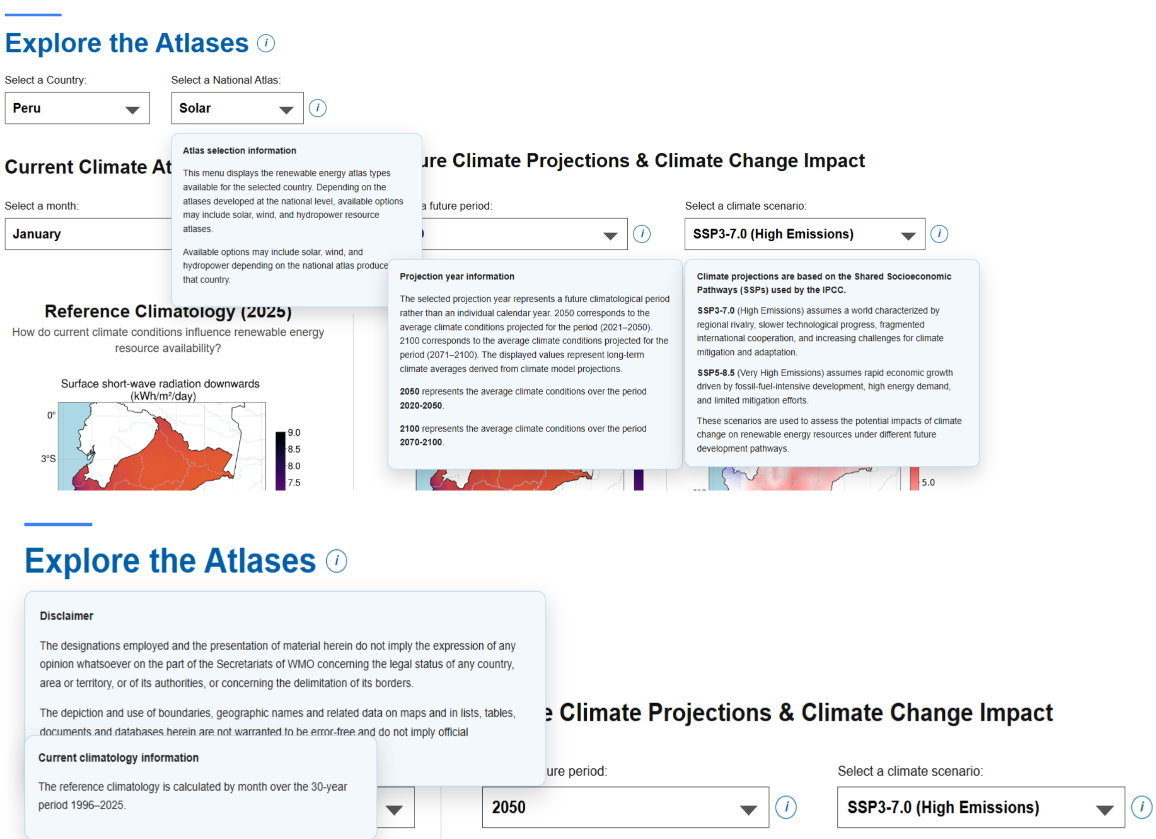


Figure 3: Screenshot of the HTML webpage: information pop-ups

Project Resources and Capacity Development Materials

Resources and support provided to participating countries

1. **Technical Documentation and Guidelines**
   - **Computer set up document:** Anaconda Navigator download and environments installation.
   - **WMO Guidelines:** A step-by-step operational manual for developing National Renewable Energy Atlases, covering data acquisition, AI-based downscaling, atlas generation, and interpretation of results. The guidelines are fully aligned with the project's open-source Jupyter notebooks. A Spanish translation will also be made available.
   - **Scientific Article:** The scientific backbone of the initiative, describing the co-production framework, AI-based downscaling methods, climate data processing workflow, and renewable energy assessment methodologies implemented throughout the project.
2. **Open-Source Codes, Data and Tools available via GitHub .**
   - **Jupyter Notebooks** supporting data processing, atlas generation, and visualization for current and future climate conditions.
   - **Supporting Resources:** accompanying datasets, shapefiles, technical documentation, setup files, and step-by-step instructions required to reproduce the atlas development workflow and associated analyses.
3. **Capacity Developement**
   - Tailored **Co-development sessions** with national institutions and stakeholders.
   - **Recorded training sessions:** covering methodology, implementation, and operational use of the atlases.
   - Recorded dissemination webinar on the methodology and results of the current phase of the project

Pilot Countries

Background

A global WMO assessment identified significant gaps in the availability of high-resolution renewable energy resource information. Many countries lack national renewable energy atlases, while existing products often do not incorporate climate projections or provide the spatial resolution required for planning and investment decisions. In response, WMO launched the National Renewable Energy Atlas Initiative to support Members in developing nationally owned, climate-informed wind, solar, and hydropower atlases through an open-source and scalable framework. To learn more about previous phases and related activities, visit the WMO Energy and Meteorology Portal: .

Initiative Timeline

***Phase I (2024)** – Methodology Development and Pilot Demonstrations*

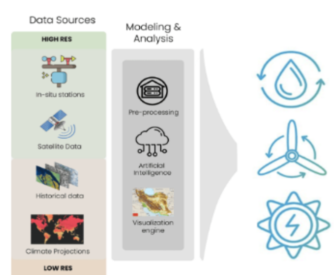
Development of the co-production framework, technical methodology, open-source tools, and training materials through pilot countries: Chile, Costa Rica, Iran, and Malawi.

***Phase II (2025)** – Expansion and Guidelines publication*

Delivery of technical webinars, training activities, and capacity development support involving NMHSs and energy-sector stakeholders from Tanzania, Croatia, and Cuba. Publication of the WMO Guidelines, open-source codes, and implementation procedures.

Phase III (2026) – *Expansion*

Deployment through the ENANDES and ENANDES+ projects, supporting the development and operationalization of National Renewable Energy Atlases in Chile, Peru, Argentina, Bolivia, and Ecuador.



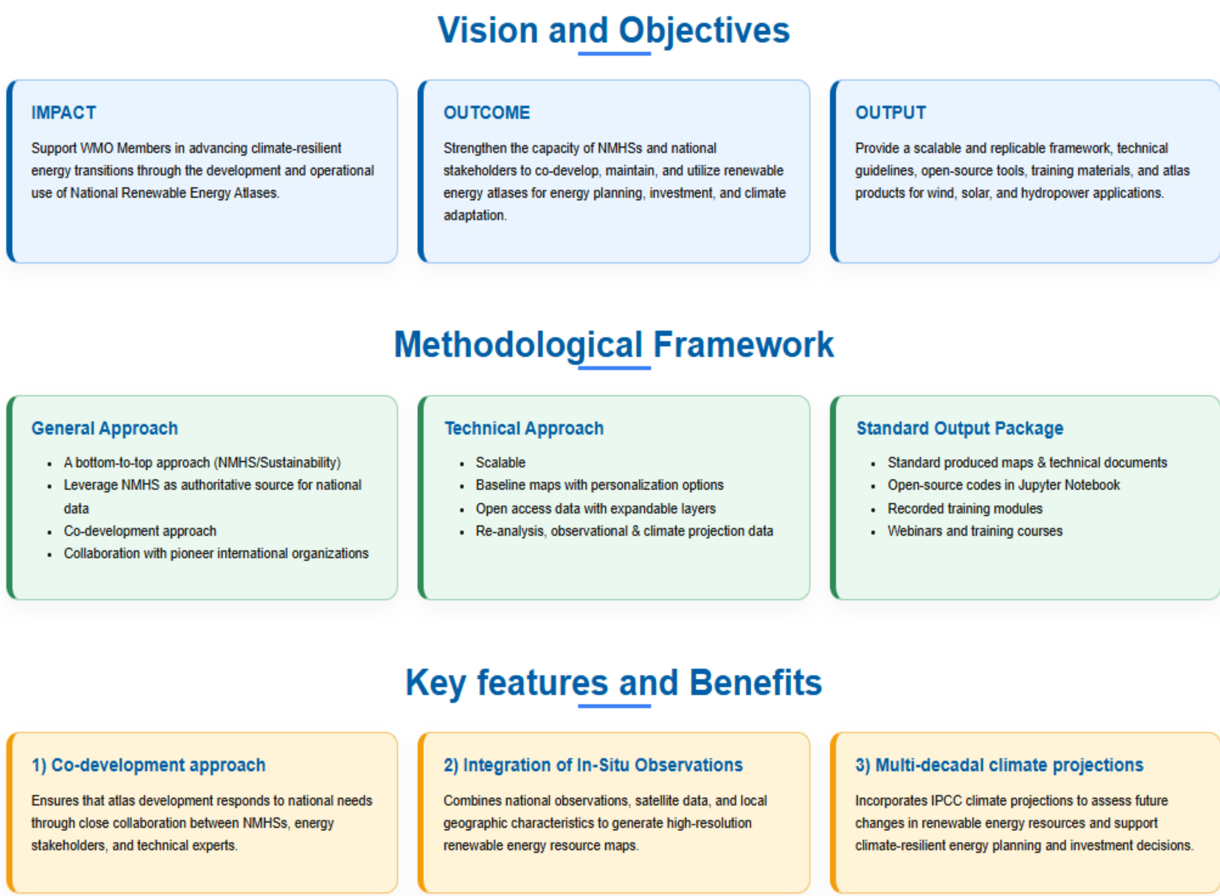
Identifying the gap

- More than 100 WMO Members participated in a global assessment of renewable energy information needs (WMO Energy Survey)
- Only a limited number of countries have operational national renewable energy atlases.
- Existing atlases are often outdated, cover only selected technologies, or do not account for climate change.
- Many NMHSs require technical guidance, tools, and capacity development to support the energy sector.
- Growing demand for climate-informed energy planning requires reliable, nationally owned renewable energy information.

National Renewable Energy Atlases support:

- Renewable energy resource assessment
- Energy infrastructure planning
- Climate-resilient energy transition
- Public and private investment decisions
- Long-term energy strategies and roadmaps
- Water-Energy-Food-Ecosystem Nexus planning
- National climate adaptation and NDC implementation

Figure 4: Screenshot of the HTML webpage: material and tools, and background on the NRA project..



Vision and Objectives

IMPACT

Support WMO Members in advancing climate-resilient energy transitions through the development and operational use of National Renewable Energy Atlases.

OUTCOME

Strengthen the capacity of NMHSs and national stakeholders to co-develop, maintain, and utilize renewable energy atlases for energy planning, investment, and climate adaptation.

OUTPUT

Provide a scalable and replicable framework, technical guidelines, open-source tools, training materials, and atlas products for wind, solar, and hydropower applications.

Methodological Framework

General Approach

- A bottom-to-top approach (NMHS/Sustainability)
- Leverage NMHS as authoritative source for national data
- Co-development approach
- Collaboration with pioneer international organizations

Technical Approach

- Scalable
- Baseline maps with personalization options
- Open access data with expandable layers
- Re-analysis, observational & climate projection data

Standard Output Package

- Standard produced maps & technical documents
- Open-source codes in Jupyter Notebook
- Recorded training modules
- Webinars and training courses

Key features and Benefits

1) Co-development approach

Ensures that atlas development responds to national needs through close collaboration between NMHSs, energy stakeholders, and technical experts.

2) Integration of In-Situ Observations

Combines national observations, satellite data, and local geographic characteristics to generate high-resolution renewable energy resource maps.

3) Multi-decadal climate projections

Incorporates IPCC climate projections to assess future changes in renewable energy resources and support climate-resilient energy planning and investment decisions.

Figure 5: Screenshot of the HTML webpage: extra information on the NRA project.

Draft conference paper

To spread the results of the third phase of the NRA initiative supported by the ENANDES and ENANDES+ projects, a conference paper, covering the updated methodology and the results, have been prepared. A potential conference to present the paper needs to be identified by WMO, hence the draft is structured in a general and standard way as follows.

National Renewable-energy atlases in a changing climate: the Latin America case

Authors: Sara Dale Gesso (AMIGO Srl), Alessandro Moser (AMIGO Srl), Hamid Bastani (Consultant, World Meteorological Organization)

Introduction

The global transition towards renewable energy requires reliable climate information, such as Renewable Energy Atlases for wind, solar, and hydropower to support long-term planning and climate-resilient investments. Although many countries have already developed renewable energy atlases, several National Meteorological and Hydrological Services (NMHSs) still rely on outdated products or lack national atlases altogether, particularly those including future climate projections. This gap limits the integration of climate change information into energy planning and infrastructure development.

To address these challenges, the third phase of the World Meteorological Organization (WMO) National Renewable-energy Atlas (NRA) initiative was implemented within the ENANDES and ENANDES+ projects, focusing on five pilot countries in South America: Argentina, Bolivia, Chile, Ecuador, and Peru. Building upon the methodologies developed during the previous phases of the initiative, the project aimed to co-develop with National Hydro-Meteorological Services (NHMSs) high-resolution NRAs for solar, wind, and hydropower resources under both present and future climate conditions. Particular emphasis was placed on producing an operational, open-source, and scalable framework that could be maintained and further developed by the participating NMHSs beyond the project lifetime.

Data & Methods

The adopted methodology, extensively described in [1], follows a user-centred co-design approach to ensure that the developed products address the specific priorities of each Country. The co-design approach entails the following steps: (i) the identification of key stakeholders to be engaged and the key objectives of the co-production process through a bilateral meeting with the NHMS; (ii) the cataloguing of available in-situ observations to be integrated into the NRAs through a structures survey; (iii) capacity building concerning the developed material within a co-production workshop. Such an approach ensures usability and usefulness of the material and tools.

The NRAs are developed by utilising an established methodology combining open-access climate datasets, in-situ observations, and machine-learning techniques within a standardized computational workflow [2]. To develop the atlases for both present and future climate conditions, the methodology builds on a variety of authoritative, open-source data reported in Table 1.

Type	Source	Variable	Usage in the Atlas
Reanalysis	ERA5Land [3]	Surface Solar Radiation Downwards, U and V component of 10m wind	Solar, Wind
Reanalysis	ERA5 [4]	Surface Solar Radiation Downwards, 2m Temperature, Total Cloud Cover U and V component of 10m wind	Solar, Wind
Reanalysis	GloFAS [5]	River Discharge	Hydropower
Satellite	CERES [6]	Global Horizontal Irradiance	Solar
Climatology	IRI [7]	U and V components of Wind	Wind
Digital Elevation Model (DEM)	ERA5Land	Orography, Aspect	Solar, Wind
DEM	GLO-90 [8]	Orography, Aspect	Solar, Wind
Shapefile	HydroSHEDS [9]	HydroBASINS	Hydropower
Shepefile	HydroSHEDS [10]	HydroRIVERS	Hydropower
Coupled Model Intercomparison Project version 6 (CMIP6)	CNRM-ESM2-1 model[HB1] [11]	Surface Solar Radiation Downwards, 2m Temperature, Total Cloud Cover, U and V component of 10m wind, River Discharge	Solar, Wind, Hydropower

Table 1. *Input datasets used for the generation of the National Renewable Energy Atlases (NRAs), including data source, variables, and application to solar, wind, and hydropower assessments.*

Figure 1 and 2 illustrate the workflow to obtain solar and wind NRAs, and hydropower NRAs, respectively. For solar and wind energy, a downscaling pipeline based on a Multi-Layer Perceptron (MLP) is used to derive 90m-resolution maps from coarse-resolution re-analysis outputs and topographic predictors. In situ observations are gridded through inverse distance weighting (IDW) interpolation, and then assimilated into the outputs of the Machine-Learning based downscaling. By contrast, the hydropower workflow operates at the hydrological basin scale, where river discharge is aggregated within HydroSHEDS catchments and corrected using available station observations through weighted averaging. Future renewable energy potential is estimated by applying the same downscaling procedure as in the present-day climate to both climate scenarios (SSP3-7.0 and SSP 5-8.5 [12]) and historical simulations, deriving the difference between the two and integrating it to the present-day maps. For solar and wind NRAs, the integration is performed through a sum, while, for hydropower NRAs through the corresponding percentage.

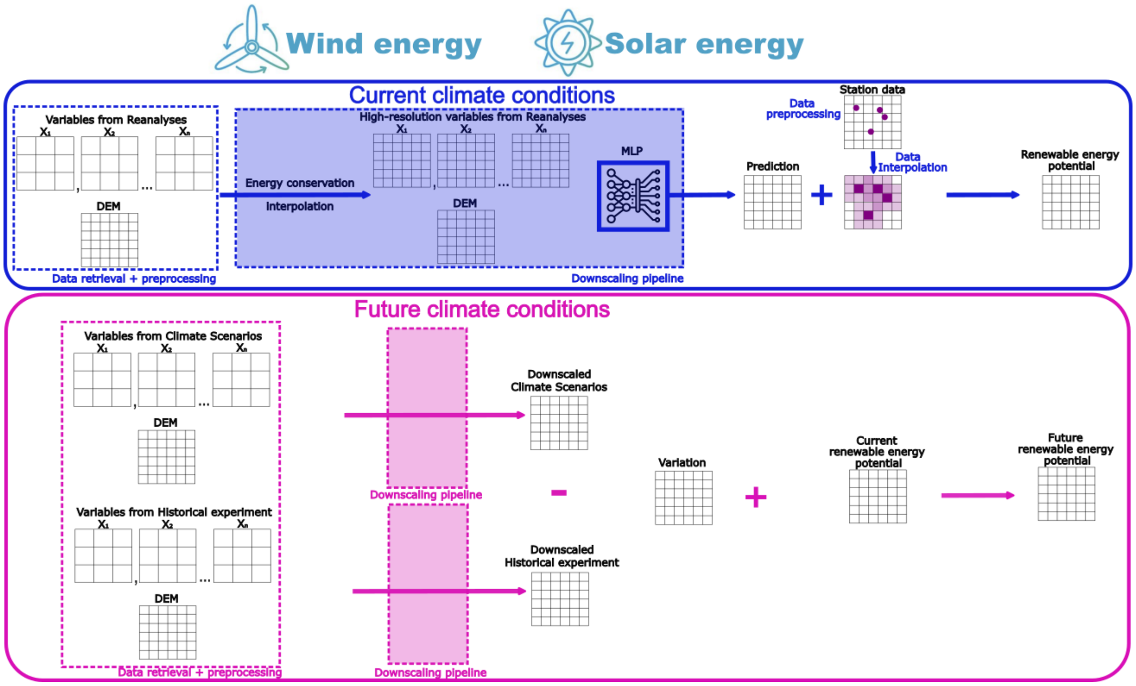


Figure 1. *Workflow developed for the generation of high-resolution solar and wind National Renewable Energy Atlases (NRAs) under present and future climate conditions.*

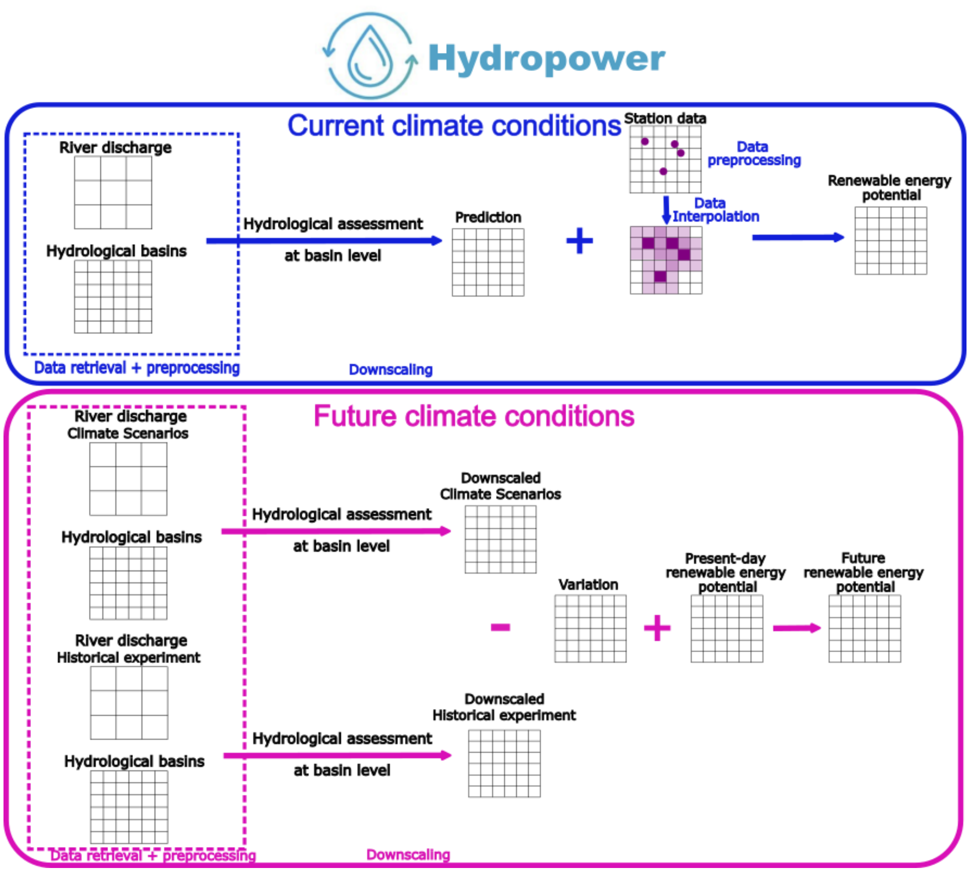


Figure 2. Workflow developed for the generation of high-resolution hydropower National Renewable Energy Atlases (NRAs).

Results and Discussion

The previously described method has been applied to develop two solar NRAs (for Argentina and Perù), two hydropower NRAs (for Bolivia and Ecuador), and one wind NRA (for Chile). Present-day outputs are derived from monthly climatologies computed over the 1996–2025 reference period. Future projections were produced for the 2020–2050 and 2070–2100 periods, using 2050 and 2100 as the respective reference time horizons. To this end, the CNRM-ESM2-1 model [11] from the Coupled-Model Intercomparison Project version 6 (CMIP6) was used to generate projections under the SSP3-7.0 and SSP5-8.5 climate scenarios.

Figures 3-7 depict representative outputs as maps of renewable potentials for present-day (left-hand side panel) and the anomaly expected for future climate conditions (right-hand side panel): Figure 3 illustrates the wind Atlas of Chile, Figure 4 the solar Atlas of Argentina, Figure 5 the solar Atlas of Peru, Figure 6 the hydropower Atlas of Bolivia, and Figure 7 the hydropower Atlas of Ecuador. The anomaly maps represent annual mean percentage changes for the 2050 time-horizon, calculated over the 2020-2050 period under the SSP3-7.0 scenario, and relative to the present climate. Although projections were generated for both SSP3-7.0 and SSP5-8.5, the spatial patterns and overall conclusions are found to be consistent across the two scenarios. Therefore, only the SSP3-7.0 results are presented for brevity.

For solar and wind Atlases (Fig. 3-7), the present-day maps are generated at 90 m spatial resolution, enabling identification of microclimatic effects on renewable energy resources. The advantage of high-resolution results is particularly noticeable over highly complex terrains such as the Andean region, where valleys can be distinguished. Other local effects can be identified, such as the high solar energy potential along the Andes in Peru and Argentina (Fig. 4-5), and a strong wind energy potential in southern Chile and the Pacific islands (Fig. 3). Similarly, the high-resolution sub-basin representation adopted for the hydropower Atlases provides a detailed overview of river discharge patterns, identifying the main contributing rivers and tributaries in Bolivia and Ecuador (Fig. 6-7). River discharge progressively increases downstream towards the Pacific Ocean in Ecuador, while in Bolivia the highest values are found in the north-eastern catchments belonging to the Amazon River basin.

The right-hand side panels of Figure 3-7 display the anomaly in percentage in renewable-energy potential for future climate conditions with respect to present-day climate. Future climate projections provide valuable information for long-term energy planning. Figure 3 highlights a net increase in wind-energy potential throughout Chile, which is qualitatively consistent with [13]. The authors of [13] reported a strengthening of the coastal southerlies under future climate scenarios, driven by an enhanced alongshore pressure gradient associated with changes in the South Pacific subtropical anticyclone. In Peru (Fig. 5), the positive solar radiation anomaly over the Amazon might be [HB3] considered consistent with observations of reduced precipitation reported by the Peruvian NHMS (personal communication). The heterogeneous solar energy potential anomaly projected over

Argentina (Fig. 4) is consistent with the spatial variability reported in [14]. In Ecuador (Fig. 7), positive hydropower potential anomalies are projected over the western basins, whereas eastern catchments draining towards the Amazon show predominantly negative changes. Conversely, Bolivia displays generally positive anomalies over the north-eastern basins flowing towards the Amazon River (Fig. 6). These patterns are consistent with the continental-scale hydrological projections reported by [15].

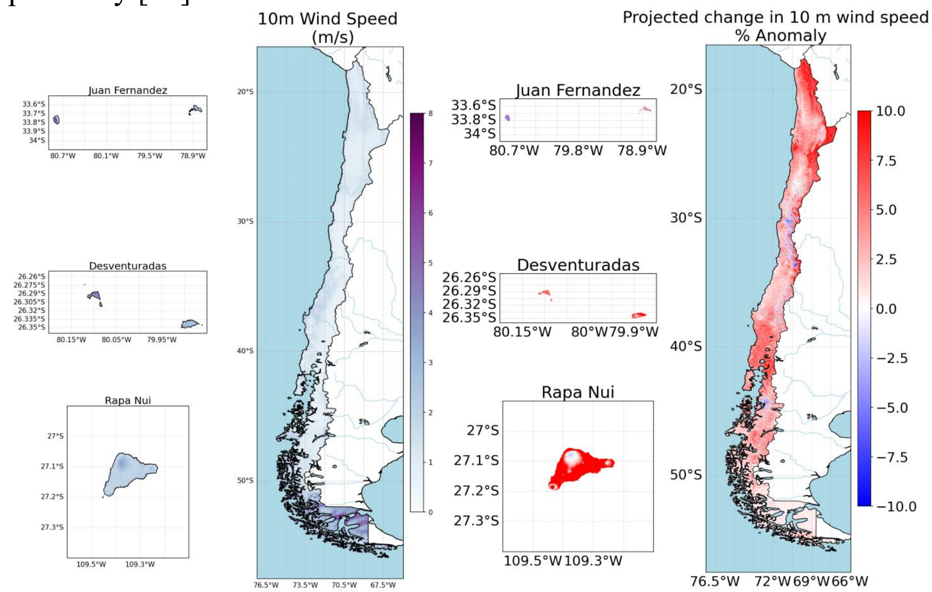


Figure 3. *Present-day mean wind speed (left) and projected annual mean wind speed anomaly (%) under SSP3-7.0 for the 2020–2050 climatological period (right) over Chile.*

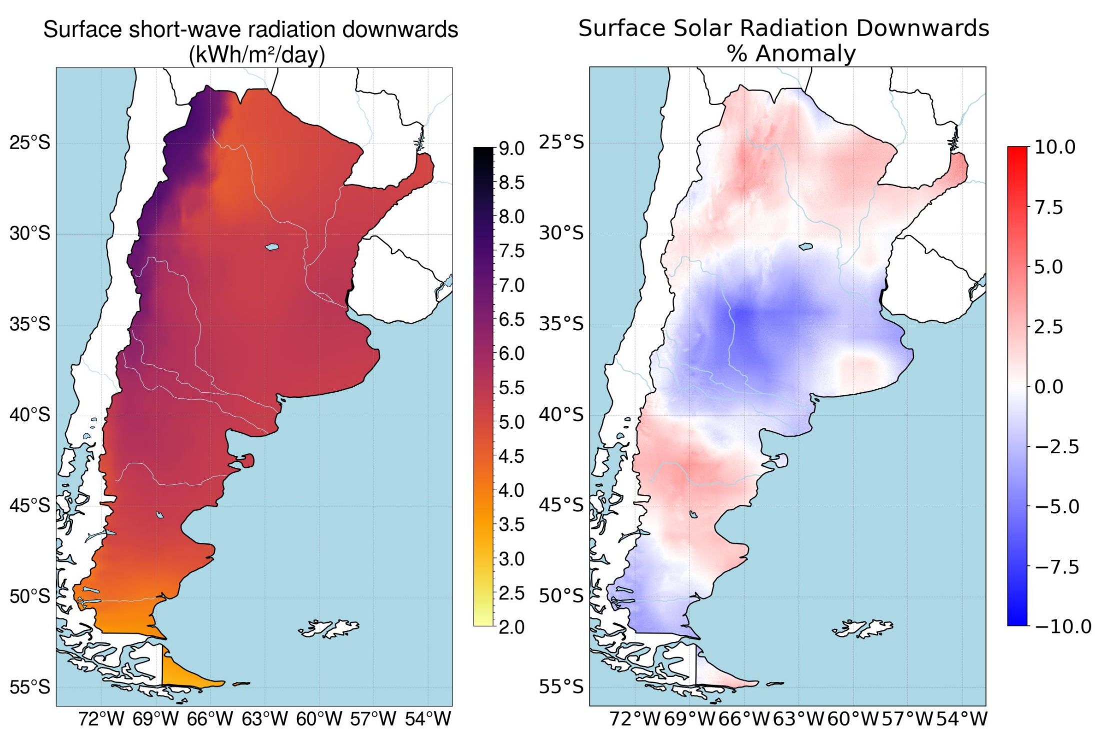


Figure 4. *Present-day mean surface solar radiation downwards (SSRD) (left) and projected annual mean SSRD anomaly (%) under SSP3-7.0 for the 2020–2050 climatological period (right) over Argentina.*

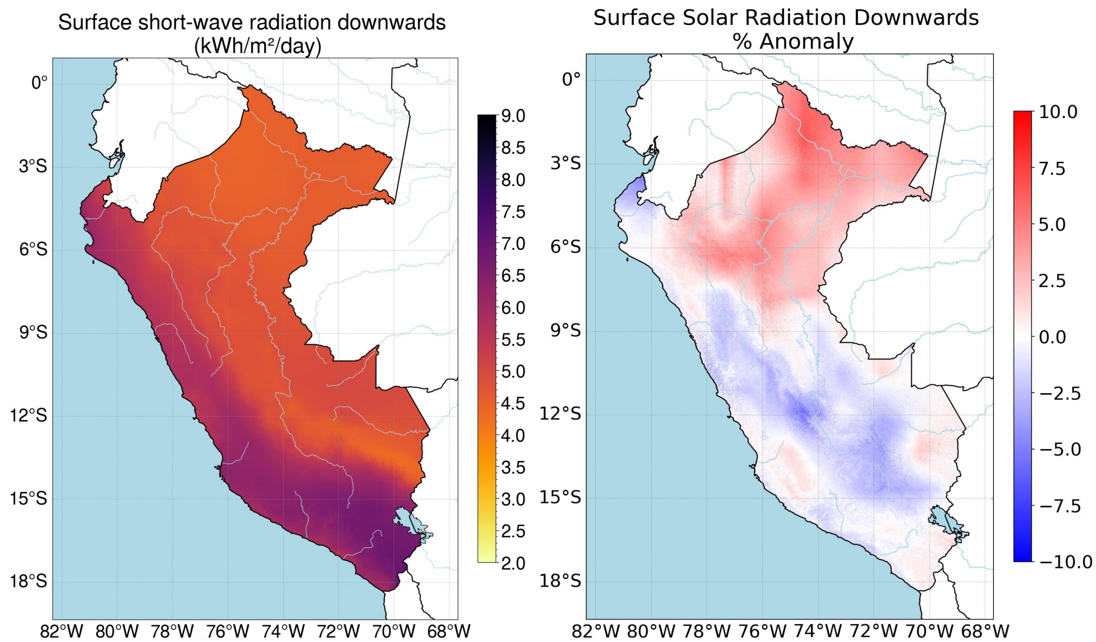


Figure 5. *Present-day mean surface solar radiation downwards (SSRD) (left) and projected annual mean SSRD anomaly (%) under SSP3-7.0 for the 2020–2050 climatological period (right) over Peru.*

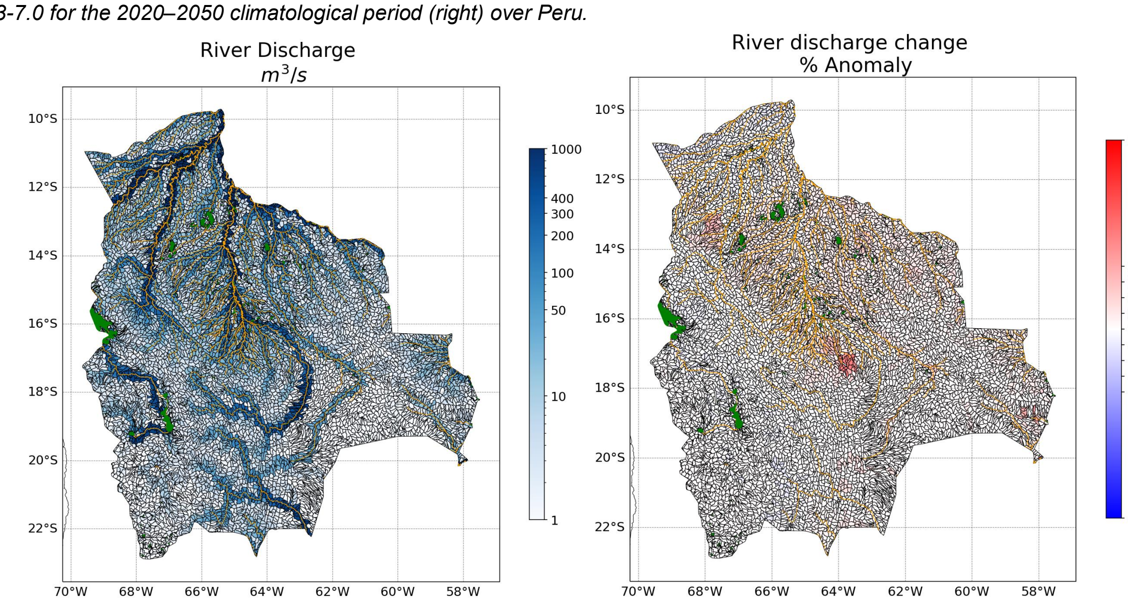


Figure 6. *Present-day river discharge (left) and projected annual mean river discharge anomaly (%) under SSP3-7.0 for the 2020–2050 climatological period (right) over Bolivia.*

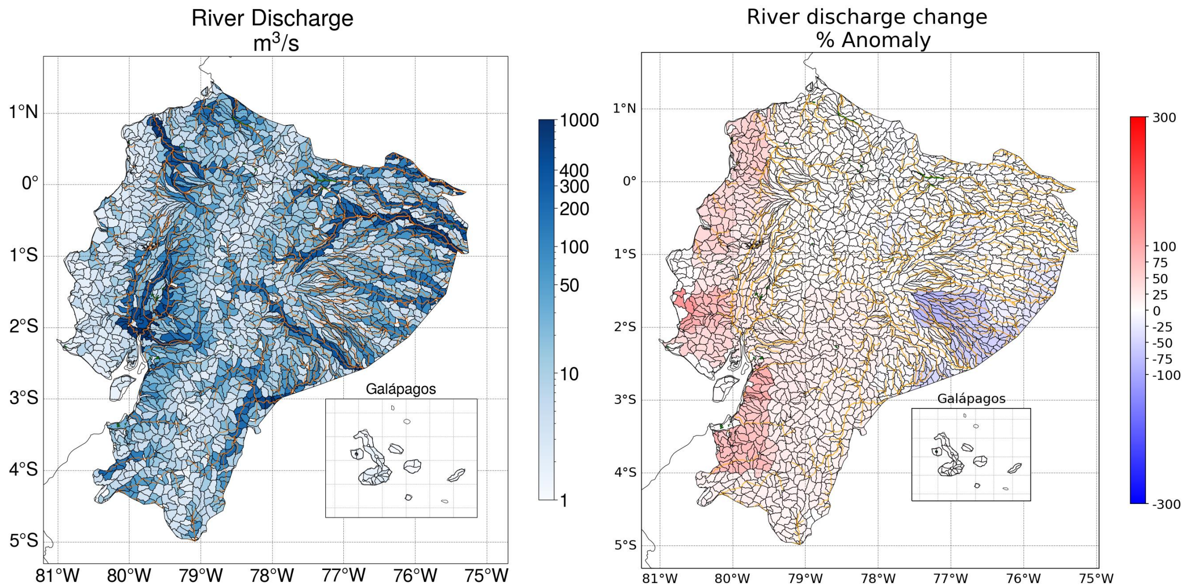


Figure 7. *Present-day river discharge (left) and projected annual mean river discharge anomaly (%) under SSP3-7.0 for the 2020–2050 climatological period (right) over Ecuador, including the Galápagos Islands.*

Conclusions

This work presents the application of a scalable methodology for the co-development of National Renewable Energy Atlases for wind, solar and hydropower under both present and future climate conditions in five Latin America countries, i.e. Argentina, Bolivia, Chile, Ecuador, and Peru. Through a structured participatory co-development process including dedicated capacity-building activities, the workflow was successfully transferred to the National Meteorological and Hydrological Services (NHMSs), enabling end-users to validate, reproduce, and further customize the methodology according to their national requirements and available datasets. The workflow, provided as Python-based Jupyter Notebooks, combines pen-access climate datasets, national observations and climate projections into a standardized framework. It also includes a digital factsheet for each country and an HTML webpage to showcase the results, available at https://crc-osa.ciifen.org/en/CST/. The underlying methodology builds on the Machine-Learning algorithm to increase spatial resolution of solar and wind energy potential, and of dedicated downscaling using basin information for hydropower energy potential. The results are further enhanced by assimilating in-situ observations of the NHMSs. The comprehensive pipeline enables the users to reach a 90m resolution. As such, the proposed workflows provide a substantial improvement over previously available atlas products at country level, which, when available, presented a much lower spatial resolution. Another key improvement with respect to the available resources at country level is the availability of projected changes in renewable energy potential in a future climate. This key resource is essential for long-term planning towards a resilient transition.

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Policy brief

The outputs of the third phase of the WMO NRA initiative, includes a policy brief, with a regional perspective, targeting the decision maker of South America. The policy brief highlights the added value of integrating long-term climate information into renewable energy atlases to inform strategic energy planning and provide recommendations on how to enhance the impact of these atlas products to be incorporated into national and regional energy and climate strategies. The draft policy brief is included below.

High-resolution National Renewable Energy Atlases as the foundation for a resilient transition – the Latin America case

Authors: Sara Dale Gesso (AMIGO Srl), Hamid Bastani (Consultant, World Meteorological Organization)

Executive summary

Latin America stands at a critical juncture in its energy transition, currently trailing the ambitious milestones established by the Paris Agreement and Sustainable Development Goal 7. Bridging this gap requires moving beyond high-level commitments toward the deployment of advanced climate intelligence capable of ensuring both a rapid shift to renewables and robust resilience against climate change. The ENANDES and ENANDES+ projects funded by the Adaptation Funds and the Swiss Agency for Development and Cooperation (SDC), respectively, and implemented by the World Meteorological Organization (WMO) address this challenge of synergizing energy adaptation and mitigation efforts by embedding the third phase of the WMO National Renewable Energy Atlas (NRA) initiative. By adopting a user-centric approach, the NRA initiative has fostered a vibrant climate-energy community in the region while creating a toolkit that integrates computational intelligence – such as AI-enhanced processing for complex, diverse climate data, including in-situ observations – with intuitive communication frameworks. The project provides a vital foundation for regional standardization, offering a unified method, consistent data formats, and accessible visualization blueprints that transform raw meteorological data into the actionable insights necessary for a sustainable and climate-proof energy future. Based on the experience built during the project in Argentina, Bolivia, Chile, Ecuador, and Peru, we make the following key recommendations:

- Strengthening collaboration among the energy and climate communities for supporting a resilient transition in the region.
- Prioritising collection and use of in-situ hydrometeorological data
- Creating a standard for climate services, including data format, visualisation and information provision.
- Enhancing AI-based methods for innovative data processing and easing accessibility.

Setting the scene

The global energy transition is anchored in the ambitious targets of the Paris Agreement and Sustainable Development Goal 7, which mandate a rapid, systemic shift toward climate-neutral and affordable energy by 2050. Despite these clearly defined international commitments, global progress remains insufficient to limit warming to 1.5°C, revealing a persistent gap between high-level policy declarations and concrete, on-the-ground implementation. Current trajectories indicate that, while political momentum is building, the pace of execution is still falling short of the speed required to secure a resilient energy future.

Latin America possesses a unique, structural advantage in the global energy transition, characterized by world-class renewable resources and an electricity generation mix already 70% powered by clean energy [1]. Yet, this inherent promise is currently obstructed by a complex paradox: while the region excels in clean generation and critical mineral supply, it remains entangled in “dual energy-dependency” and fragmented policy frameworks that hinder systemic progress. Despite commendable efforts in specific Countries, the region’s overall transition pace lags behind global benchmarks. With energy system scores virtually stagnant over the last decade and investment falling critically short – attracting only a fraction of the $150 billion annual requirement by 2030 [1] – the region faces a widening gap between its natural, carbon-neutral promise and the reality of its current economic and policy landscape.

Beyond structural policy hurdles, the energy transition faces acute, emerging risks from accelerating climate variability and change. 2024 underscores this vulnerability: global temperatures have overcome the 1.5°C threshold, with climate anomalies increasingly disrupting the performance of wind, solar, and hydropower infrastructure [2]. South America has been particularly exposed, experiencing energy demand spikes exceeding 20% and persistent drought-induced deficits that threaten hydropower stability [2]. These events demonstrate that climate volatility is no longer a peripheral concern but a central driver of energy insecurity. To enforce a resilient transition, policymakers must urgently integrate long-term climate information into their strategic energy planning to support synergic implementation of adaptation and mitigation actions at all governance levels, mapping renewable energy potential in a changing climate for hydropower, wind and solar.

ENANDES and ENANDES+ as a seed for building a climate-resilience energy community

ENANDES (Enhancing Adaptive Capacity of Andean Communities through Climate Services) and ENADES+ are key examples of projects that support synergic adaptation and mitigation action for vulnerable communities. Focusing on the Andean region, the activities of the two projects aim at enhancing adaptive capacity at all levels, from local communities to continental collaborations, including both the reduction of the adverse impacts and benefitting from favourable conditions due to climate change. Four major outcomes have been achieved:

- **Enhancing capacities** of the National Meteorological and Hydrological Services (NMHSs) to timely communicate actionable information;
- **Developing partnerships and strengthening linkages** with national and local climate-sensitive institutions in agriculture, energy and water sectors;

Figure 1: maps illustrating the pilot countries participating in the initiative and the NRAs developed in the third phase of the NRA project within ENANDES and ENANDES+.

- **Demonstrating adaptation activities** using climate services in various sites;
- **Coordinating and liaising** with regional and global organizations.

With the overarching goal of addressing climate change impact and embracing emerging opportunities in the energy sector, ENANDES and ENANDES+ incorporate a specific activity focused on the development of National Renewable-energy Atlases (NRAs). The NRA initiative was launched by WMO in response to the needs for high-quality and high-resolution climate information on renewable energy resources in a changing climate. The primary goal of the NRA initiative was to co-develop a comprehensive technical framework, step-by-step guidance, and a practical, scalable and open-access tool for the systematic creation of national atlases for wind, solar and hydropower resources, for current and projected climate under different emission scenarios. The third phase of the NRA initiative builds on the material and method designed in the previous years with a specific geographical scope on Latin America, focusing on Argentina, Bolivia, Chile, Ecuador and Perù as pilot Countries (Fig.1).

Embracing a user-centric approach [3], the third phase of the NRA initiative within ENANDES and ENADES+ projects was structured along three cornerstones:

- **Co-design and personalization** based on identification of specific needs through bi-lateral meetings with the countries, i.e. National Hydrological and Meteorological Services (NHMSs), and other national stakeholders of the energy sector;
- **Co-production** towards capacity building aiming at demonstrating the whole toolkit including open source Jupyther Notebooks and supporting materials;
- **Face-to-face engagement** to promote the wider adoption of the method and build the foundation to the follow-up phases of the initiative (e.g. Assunciòn, Paraguay, November 2025).

These activities not only ensure that the outputs of the project are usable and useful for the countries, but also support the creation of a blended energy and climate community across the region.

The Observational Backbone – Advancing In-Situ Data for Climate-Smart Energy Decisions
The WMO NRA is committed to open-source data, and leverages on the wealth of information available globally, including satellite observations, model-based re-analyses, and the IPCC climate projections. However, the precision of any renewable energy atlas at local scale fundamentally rests upon a dense, reliable network of *in-situ* hydrometeorological observations [4]. This ground-level intelligence is indispensable, particularly in complex terrain like the Andes, where dramatic orography generates highly localized microclimatic conditions that coarse-resolution gridded data invariably smooth over. Without the specific reality captured by these stations, energy planning risks being built on broad assumptions that overlook the variability of wind, solar, and hydrological resources within mountain valleys and slopes.

Currently, the South American network of hydrometeorological data counts more than 14,000 stations, unevenly distributed among Countries [5]. The activities of Countries are synergised at regional level through two WMO Regional Climate Centers (RCC): the RCC for Western South America (RCC-WSA), and the RCC for Southern South America (RCC-SSA). WMO Regional Climate Centres (RCCs) are centres of excellence mandated to generate high-quality regional-scale climate products to support development and delivery of effective climate services at a national scale.

Despite the continuous efforts of NHMSs, the current continental network of hydrometeorological stations remains significantly under-resourced, particularly in remote areas where the most vulnerable populations reside. This sparse coverage creates critical blind spots, compromising the quality of climate intelligence precisely where it is needed most for resilient energy planning. Another common gap in climate data is the absence of a unified, standardized quality control framework which results in fragmented and unreliable data, undermining its utility for strategic decision-making in the energy sector and beyond. Just as crucial is the untapped potential of the reservoir of observational data from power plants and energy infrastructure, which are generally privately owned, restricted datasets. Formal, mutually beneficial agreements between NMHSs and energy operators could fortify the observational backbone and, hence, the quality and reliability of sectorial climate services.

Addressing the existing deficiencies is not merely an operational task. It is a fundamental prerequisite for ensuring that climate-smart energy solutions are equitable, accurate, and truly representative of the diverse territorial realities across the continent. Realizing this goal requires a substantial increase in dedicated financial resources to expand the density of observational networks and provide the long-term support necessary to maintain high-quality data standards. Virtuous examples of framework to support observational network expansion are the Systematic Observations Financing Facility (SOFF) – a UN Fund co-created by WMO, UNDP and UNEP to close the climate and weather observations data gap – and the Observing Systems Capability Analysis and Review Tool (OSCAR) – a resource developed by WMO in support of Earth Observation applications, studies and global coordination. However, without further sustained funding, the region risks leaving critical infrastructure gaps unaddressed, undermining the reliability of the climate intelligence needed to navigate an uncertain future.

Climate services as a common ground for accelerating the energy transition

To transform the wealth of data into actionable information, the energy sector needs tailored *climate services*, which are defined by WMO as the provision and use of climate data, information and knowledge to assist decision-making. The international effort toward integrating science-based climate information and prediction into planning, policy and practice is embodied by the Global Framework for Climate Services (GFCS), established more than a decade ago as a multi-governmental and multi-stakeholder partnership. Considering the inherent dependency of renewable energies to weather and climate, it is not surprising that the global energy transition demands a paradigm shift toward advanced weather, water, and climate information and services that translate complex data into actionable decision-support. These services act as the bedrock of energy security, enabling operators to mitigate climate-related shocks and optimize efficiency through proactive risk assessments [6]. Furthermore, such climate intelligence is indispensable throughout the energy lifecycle, guiding critical decisions in site selection and resource financing, optimizing daily operations and maintenance, and ensuring seamless integration into the power grid.

The ENANDES and ENANDES+ projects have developed a comprehensive toolkit for estimating and analysing renewable energy potential for wind, solar and hydropower that embodies the definition of an effective climate service aligned with the Global Framework for Climate Services standards. This toolkit is structured into two essential components:

- ***Technical package*** featuring a suite of Jupyter Notebooks and a set of capacity building material, i.e. a user guideline document (in both English and Spanish) [7] and a recorded training session, that empower National Meteorological and Hydrological Services as well as other relevant entities to autonomously generate national renewable atlases with the flexibility to independently adapt methodologies to local needs;
- ***Communication package*** which specifically targets the energy sector, and presents complex results through an intuitive Graphic User Interface hosted on the WMO portal, complemented by dedicated factsheets designed to distil high-level insights for non-technical energy stakeholders, thereby ensuring that rigorous scientific intelligence directly informs actionable policy and public discourse.

Beyond providing individual technical solutions, the climate service package developed within the ENANDES and ENANDES+ projects lays a critical foundation for continental-level synergies and collaborations. By establishing a common standard for calculating NRAs – including a unified methodological framework, consistent data format needs, and a standardized visualization blueprint – this initiative enables NMHSs across the region to adopt a shared technical language. This alignment not only streamlines cross-border knowledge exchange but also ensures that energy planning and climate adaptation strategies are built upon a cohesive, interoperable base, effectively transforming isolated national efforts into a unified continental response.

Harnessing Artificial Intelligence for Energy Transformation

The potential of artificial intelligence (AI) to transform climate resilience is vast, offering a sophisticated portfolio of options to address systemic challenges from mitigation to adaptation. By unifying fragmented data streams – such as those from policy planning, resource allocation, and capital distribution – AI serves as a powerful platform for integrating global information to develop cohesive, cross-border solutions [8]. The methodology underpinning the WMO NRAs is specifically designed to leverage these capabilities, i.e. capitalise on fragmented data streams to uncover hidden, complex relationships. This advanced approach is particularly vital for resolving the intricate dynamics of atmospheric circulation at small, local scales, where conventional models would require massive computational resources to perform adequately.

However, AI, especially Generative AI, opens up further excellent opportunities for energy transformation. It offers a transformative opportunity to close the gap between climate intelligence providers and final users, especially vulnerable populations [9] – such as the Andeans communities at the centre of ENANDES and ENANDES+ – by translating complex climate information into accessible, plain-language insights that can be readily understood and utilized. In general, these technologies unlock new digital avenues for the equitable dissemination of climate information, ensuring that actionable intelligence is accessible, meaningful, and genuinely empowering for the communities at the frontlines of the climate crisis. They serve as a catalyst for mainstreaming climate services across all domains, including the energy sector, hence directly propelling the pace of the energy transition. However, the deployment of these technologies must be rooted in meaningful community engagement [7]. Effective climate service tools require local collaboration to ensure that proposed solutions are trusted, culturally relevant, and adaptable to specific needs.

The adoption of Generative AI is not without its own downsides linked both to the massive energy consumptions of the data centres and structural challenges, particularly concerning the inherent lack of transparency in automated decision-making, the risk of algorithmic misinformation, and the persistent barriers to digital accessibility that threaten to leave vulnerable communities behind. If left unaddressed, these issues could exacerbate existing inequities across South America, where limited digital infrastructure risks creating a technological divide between nations [10]. Navigating these obstacles necessitates a dedicated financial commitment to strengthen the region's computational foundations and digital capacity. By strategically channelling investment into both robust infrastructure and inclusive training, stakeholders can close this technological gap, ensuring that AI-driven climate intelligence becomes an equitable resource rather than a source of further fragmentation.

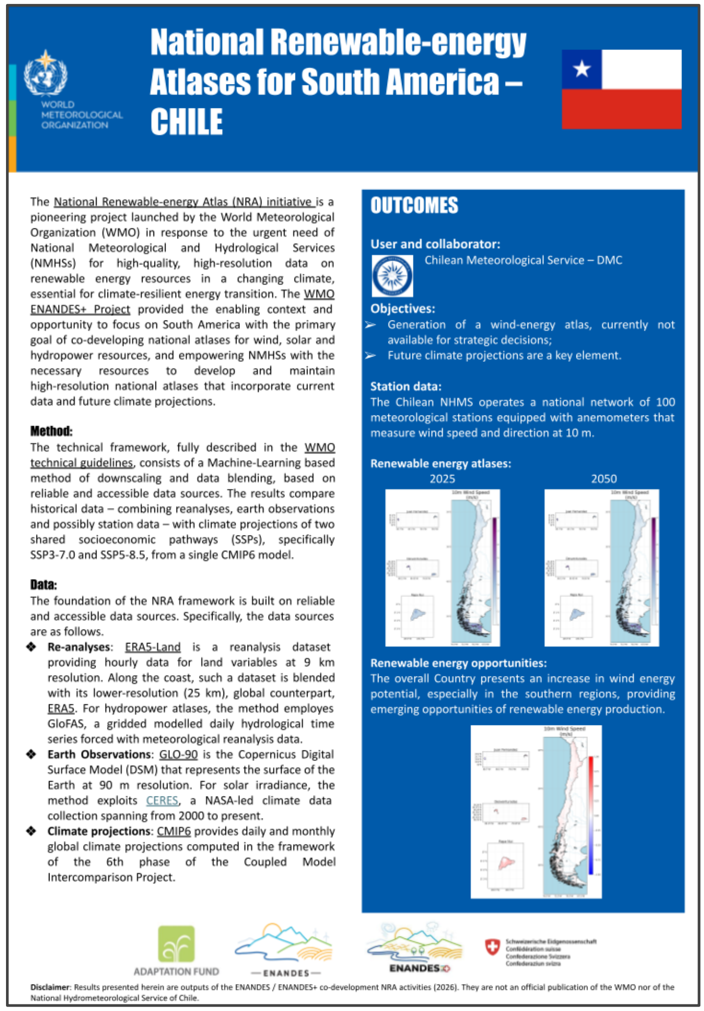
Success story: Chile

Chile exemplifies the dual promise of Latin America's energy transition. Spanning 4,300 km, the nation's diverse geography – ranging from the unrivalled solar irradiance of the Atacama Desert to the world-class wind corridors of the Magallanes region – positions it as a renewable powerhouse. This natural advantage has been instrumental in a rapidly accelerating transition: the contribution of low-emissions sources to total energy demand rose from 24% in 2010 to 38% in 2024, driven by the decisive retirement of coal assets and the aggressive expansion of solar and wind, which now account for over 34% of electricity generation [11]. Yet, despite these structural advancements, the economy remains tethered to fossil fuels, as evidenced by the USD 14 billion spent on imports in 2024, underscoring the urgent need to sustain and deepen policy-driven decarbonization efforts [11].

To support its energy transition, Chile strategically participated in the first (2024) and third (2026) phases of the NRA initiative, successfully developing national solar and wind energy atlases. Prior to this initiative, the Country could not rely on any NRA for long-term planning. Renewable energy potential was assessed only through fragmented, local observations, lacking the national-scale intelligence required for systemic planning. The transition from localized data to a comprehensive atlas framework, covering the entire country, represents a significant institutional advancement, providing the precise climate intelligence needed to underpin the country's long-term energy strategies. Moreover, the Chilean NHMS could leverage its established network of 100 meteorological stations uniformly distributed throughout the country, hence ensuring that the atlases capture realistic microclimatic conditions, particularly relevant in complex geographic and orographic conditions such as the Chilean ones.

Since 2024, the Chilean NHMS has had the opportunity to employ the technical package for the generation of the solar energy atlas. The independent application of such a technical package validated the robustness of the methodology, requiring only minor procedural adjustments for operationalisation. The provided documentation and Jupyter Notebooks facilitated a seamless workflow, enabling national teams to rapidly grasp the technical intricacies involved. Furthermore, the greater interaction between the WMO team and national counterparts during the 2026's third phase – a marked improvement over the initial pilot – significantly streamlined the resolution of technical challenges. This enhanced, iterative collaboration not only accelerates the adoption of the framework fastening the operationalisation of wind energy atlas, but also strengthens the institutional collaboration essential for its long-term success.

The solar atlas, now formally delivered to the Ministry of Energy – which directly collaborated with the Chilean NHMS for its creation –, is currently serving as a technical foundation for internal evaluation and planning processes. Beyond its immediate application, the development of the atlas has catalysed essential dialogue regarding the strategic necessity of high-resolution climate intelligence, reaffirming the value of transparent and reproducible methodologies in supporting national energy policies. This initiative has significantly deepened the institutional partnership between the Chilean NHMS and the Ministry of Energy, establishing a framework for sustained collaboration. The envisioned next step is to expand the user base, reaching other key stakeholders such as the electric system operator, other ministries, for instance the Ministry of Agriculture supporting rural development, and universities and research institutions. While the full institutionalization and public dissemination of these products remain a gradual process aligned with the NHMS's current operational capacities, the groundwork has been laid for a transformative impact on the nation's energy planning capabilities.



WORLD METEOROLOGICAL ORGANIZATION

National Renewable-energy Atlases for South America – CHILE

The National Renewable-energy Atlas (NRA) initiative is a pioneering project launched by the World Meteorological Organization (WMO) in response to the urgent need of National Meteorological and Hydrological Services (NMHSs) for high-quality, high-resolution data on renewable energy resources in a changing climate, essential for climate-resilient energy transition. The WMO ENANDES+ Project provided the enabling context and opportunity to focus on South America with the primary goal of co-developing national atlases for wind, solar and hydropower resources, and empowering NMHSs with the necessary resources to develop and maintain high-resolution national atlases that incorporate current data and future climate projections.

Method:
The technical framework, fully described in the WMO technical guidelines, consists of a Machine-Learning based method of downscaling and data blending, based on reliable and accessible data sources. The results compare historical data – combining reanalyses, earth observations and possibly station data – with climate projections of two shared socioeconomic pathways (SSPs), specifically SSP3-7.0 and SSP5-8.5, from a single CMIP6 model.

Data:
The foundation of the NRA framework is built on reliable and accessible data sources. Specifically, the data sources are as follows.

- **Re-analyses**: ERA5-Land is a reanalysis dataset providing hourly data for land variables at 9 km resolution. Along the coast, such a dataset is blended with its lower-resolution (25 km), global counterpart, ERA5. For hydropower atlases, the method employes GloFAS, a gridded modelled daily hydrological time series forced with meteorological reanalysis data.
- **Earth Observations**: GLO-90 is the Copernicus Digital Surface Model (DSM) that represents the surface of the Earth at 90 m resolution. For solar irradiance, the method exploits CERES, a NASA-led climate data collection spanning from 2000 to present.
- **Climate projections**: CMIP6 provides daily and monthly global climate projections computed in the framework of the 6th phase of the Coupled Model Intercomparison Project.

OUTCOMES

User and collaborator:
Chilean Meteorological Service – DMC

Objectives:
- Generation of a wind-energy atlas, currently not available for strategic decisions;
- Future climate projections are a key element.

Station data:
The Chilean NHMS operates a national network of 100 meteorological stations equipped with anemometers that measure wind speed and direction at 10 m.

Renewable energy atlases:
2025 2050

10m Wind Speed (m/s)

10m Wind Speed (m/s)

Renewable energy opportunities:
The overall Country presents an increase in wind energy potential, especially in the southern regions, providing emerging opportunities of renewable energy production.

10m Wind Speed (m/s)

ADAPTATION FUND — ENANDES — ENANDES+

Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

Disclaimer: Results presented herein are outputs of the ENANDES / ENANDES+ co-development NRA activities (2026). They are not an official publication of the WMO nor of the National Hydrometeorological Service of Chile.

Figure 2: factsheet of the wind-energy atlas of Chile developed during the third phase of the project.

Recommendations

The journey toward a climate-resilient energy future in South America is not a solitary technical challenge, but a collective and integrated undertaking that requires decisive policy action. On the basis of the experience gained in the 3rd phase of the WMO NRA initiative within ENANDES and ENANDES+ projects, we propose the following strategic actions:

- **Foster Cross-Community Integration:** Intentionally blend energy and climate communities to ensure strategic policy is consistently informed by precision science.
- **Prioritize In-Situ Data Collection:** Invest in high-fidelity ground observations as the essential intelligence to enhance local effectiveness of regional planning.
- **Standardize Climate Services:** Harmonize data formats, visualization blueprints, and information provision to ensure cross-border interoperability and technical cohesion.

- **Enhance AI-Driven Methodologies:** Scale innovative processing capabilities to democratize access to climate intelligence and transform complex datasets into actionable tools for all.

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IP management

Transfer of Source Code and Intellectual Property is submitted in a separate word document.

Appendix – Screenshots of the master notebook

This appendix entails some illustrative screenshots of the Master notebook designed to exemplify the methodology to policy-makers. The entire notebook is available in a dedicated GitHub.

WMO National Renewable Atlases – Demonstration for Policy Makers

This notebook is a **demonstration** of the workflow used to generate the National Renewable Atlas products.

The figures displayed in this notebook are **not final Atlas products**. They are illustrative PNG outputs prepared to explain, step by step, the methodological upgrades provided by the workflow, from global datasets to country-specific Atlas-ready information.

For clarity, one representative country and one representative variable have been selected for each Atlas type. When the user selects `ATLAS_DEMO`, the notebook automatically adapts the following steps and loads the corresponding demonstration figures.

Dataset-opening and processing commands are intentionally retained as **commented code**. This makes the data sources and processing chain transparent, while keeping the demo fast and robust for policy-maker presentations.

How to run the demonstration

1. Select the Atlas type by setting `ATLAS_DEMO`.
2. Run the notebook from top to bottom.
3. The active cells load pre-generated PNG figures.
4. Commented cells show which datasets would be opened or processed in the full production workflow.
5. The notebook is organised into **Pilot Countries**, **Present Climate**, and **Future Climate** sections.

Python packages to import

In [1]:

```
import matplotlib.pyplot as plt
import rioxarray
from pyhdf.SD import SD, SDC
import xarray as xr
import pandas as pd
import glob
import os
import geopandas as gpd
import numpy as np
from shapely.ops import cascaded_union
from shapely.ops import unary_union
from datetime import datetime
import matplotlib.patches as mpatches
import matplotlib.image as mpimg
from mpl_toolkits.axes_grid1.inset_locator import inset_axes
```

repository

Figure A1: Screenshots of the master notebook: introduction and information.

Pilot Countries

Countries included in this demonstration phase

This first step gives a geographical overview of the pilot countries included in the current phase of the National Renewable Atlas initiative.

The map is loaded as a pre-generated PNG for presentation purposes. The commented code shows how the figure can be recreated from the country shapefile.

In [2]:

```
#shapefile_path = './world_map/ne_50m_admin_0_countries.shp'
#world = gpd.read_file(shapefile_path)
#south_america = world[world["CONTINENT"] == "South America"].copy()

#pilot_colors = {"Peru": "lightcoral", "Argentina": "lightcoral","Chile": "mediumseagreen","Ecuador": "cornflowerblue","Bolivia":

#fig, ax = plt.subplots(figsize=(8, 10))
#south_america.plot(ax=ax,color="white",edgecolor="black",linewidth=0.3)
#for country, color, label in zip(list(pilot_colors.keys()),list(pilot_colors.values()),list(pilot_colors.keys())):
#    south_america[south_america["SOVEREIGNT"] == country].plot(ax=ax,label= label,color=color,edgecolor="black", linewidth=0.7)
#ax.legend()
#ax.set_title("Pilot Countries", fontsize=18, fontweight="bold")
#ax.set_axis_off()
#plt.tight_layout()
#plt.savefig('./figures/DEMO/pilot_countries.png')

### Integrate the Cartopy Map with the Image that Shows the type of renewable per country (Map with Legend)
pilot_img = mpimg.imread("./figures/DEMO/pilot_countries.png")
atlas_img = mpimg.imread("./figures/DEMO/atlases_countries.png")
fig, ax = plt.subplots(figsize=(10, 10))
ax.imshow(pilot_img)
ax.axis("off")
axins = inset_axes(ax,width="35%",      height="35%",     loc="lower left", borderpad=1)
axins.imshow(atlas_img)
axins.axis("off")
for spine in axins.spines.values():
    spine.set_edgecolor("black")
    spine.set_linewidth(1.5)
plt.tight_layout()
plt.show()
```

Figure A2: Screenshots of the master notebook: information on countries.