RENEWABLE ENERGY GIS TOOL GUIDE—INFORMING CHOICE OF TOOLS TO SUPPORT DECISIONS

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August 2019

A product of the USAID-NREL partnership
Contract No. IAG-17-2050

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This work was authored, in part, by the National Renewable Energy Laboratory (NREL), operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by the United States Agency for International Development (USAID) under Contract No. IAG-17-2050. The views expressed in this report do not necessarily represent the views of the DOE or the U.S. Government, or any agency thereof, including USAID.

Acknowledgments

The authors would like to thank Haiku Sky, Nate Blair, Dan Bilello, Galen MacLauren, and Jessica Katz of the National Renewable Energy Laboratory (NREL), as well as Oliver Knight of the Energy Sector Management Assistance Program (ESMAP) for direction and review. Any remaining errors or omissions are those of the authors.

List of Acronyms

CMSAF	Climate Modeling Satellite Application Facility
ECMWF	European Centre for Medium-Range Weather Forecasts
ERA5	European Centre for Medium-Range Weather Forecasts Re-Analysis
ESMAP	Energy Sector Management Assistance Program (World Bank Group)
GDP	gross domestic product
GIS	geographic information system
IEC	International Electrotechnical Commission
IRENA	International Renewable Energy Agency
LCOE	levelized cost of energy
MapRE	Multi-criteria Analysis for Planning Renewable Energy
NREL	National Renewable Energy Laboratory
NSRDB	National Solar Radiation Database
NGO	non-governmental organization
PV	photovoltaic
PVGIS	European Commission Photovoltaic Geographical Information System
RE	renewable energy
SARAH	Surface Solar Radiation Data Set-Heliosat
USAID	United States Agency for International Development
WBG	World Bank Group

Executive Summary

This report compares the use and functionality of six geographic information system (GIS) web applications from governmental organizations, non-governmental organizations (NGOs), and universities used to support international renewable energy (RE) development.

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1 Introduction

To support the growth in wind, solar, hydropower, geothermal, bioenergy, and marine hydrokinetic energy, several map-based web applications with interactive tool functionality have been created to support the dissemination of information on renewable energy (RE) viability in specific areas. These geographic information system (GIS) tools exist on the internet and have been created by government entities, non-governmental organizations (NGOs), and universities, and use standard industry criteria in location analysis for various energy sources. Country-level decision and policymakers can use these data and analyses to support RE planning, policymaking, and other types of decisions.

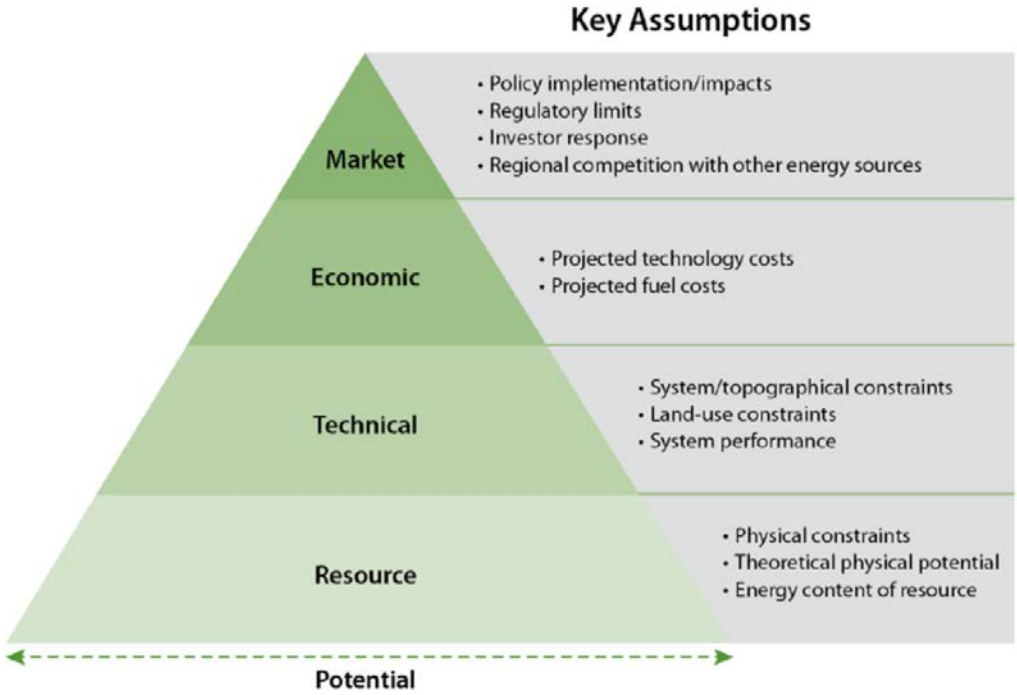

Figure 1. Renewable energy potential analyses and key assumptions

Image from Lopez et al. 2012

Many tools compared in this report focus on the Resource and Technical Potential levels of analysis in the RE potential pyramid presented in Figure 1. In this hierarchy, the base resource potential describes the inherent attributes within a resource, including its potential energy content, the physical and chemical limitations to accessing the energy contained in the resource, and its overall theoretical potential. Next in the hierarchy is technical potential, the achievable energy capacity and generation of a technology, given resource potential, system performance, topographic limitations, and environmental and land use constraints. After the technical potential, the economic potential adds a cost factor into the resource's energy access. Specifically, it defines the subset of the available resource technical potential where the cost required to generate electricity is below the revenue available in terms of displaced energy and displaced capacity. This may include costs incurred in the development of technology for resource utilization, upfront costs of installation, and ongoing maintenance.

To determine geographic areas where RE has high technical or economic potential, appropriate exclusions must be determined for the different attributes of a technology. Exclusions are geographic areas that are unfavorable toward an attribute. For example, it may be cost-effective to site a RE power plant close to existing high-power transmission lines, minimizing the construction of expensive connecting lines. In this case, a 5-kilometer buffer, or zone, could be created around power lines such that only resources within that buffer are considered in the analysis. Areas outside the 5-kilometer buffer that are unfavorable toward the attribute would then be excluded from consideration. In another example, it is generally not cost-effective to install wind technologies on slopes greater than 20 degrees, so eliminating high-slope areas from consideration would also be an exclusion.

Through these steps, general locations can be found that eliminate unfavorable geographical locations through an attribute's exclusions, have favorable RE technical potentials, and are within deterministic economic factors. The last step in the evaluation of RE resource potential is market potential. This potential considers various political and socioeconomic factors in the siting of RE technologies. As these factors can have nuanced social, cultural, political, and legal ramifications, this step depends upon the policies of the governing authorities interested in developing RE resources. For this reason, the web applications reviewed include some aspects of resource, technical, and, to a small extent, economic potential, but duly resign to address the market potential of specific sites, which should rightly be determined through sophisticated analysis by appropriate policymakers, stakeholders, and developers.

The scope of the web applications reviewed should also be noted. Half focus solely on one form of RE, (e.g., either wind or solar). The remaining tools may add bioenergy, geothermal, hydropower, and marine hydrokinetic energy, to a certain degree, for an area of study. The tools reviewed were chosen based on consultation with experts at the National Renewable Energy Laboratory (NREL), in Golden, Colorado, on geospatial tools available to support RE mapping, visualization, and analysis used widely internationally.

The following web applications were reviewed:

- Global Solar Atlas (http://globalsolaratlas.info/)
- Global Wind Atlas (https://globalwindatlas.info/)
- Multi-Criteria Analysis for Planning Renewable Energy (MapRE) (http://mapre.lbl.gov/)
- European Commission Photovoltaic Geographical Information System (PVGIS) (http://re.jrc.ec.europa.eu/pvg_tools/en/tools.html#TMY)
- International Renewable Energy Agency (IRENA) Global Atlas (https://irena.masdar.ac.ae/gallery/#gallery)
- Renewable Energy Data Explorer (RE Explorer) (https://www.re-explorer.org/)

Additionally, one website is reviewed in Appendix A. While the Climatescope 2017 site (http://global-Climatescope.org/en/) is not a RE web application per se, it does contain a wealth of information on energy use and sourcing for more than 70 countries.

2 Methods

This report starts with a qualitative description of each web application. The description includes information on user interface, capabilities, and the organizations developing the tools.

Quantifiable attributes related to the frameworks and functionalities of each tool are then summarized in Table 1 and Table 2. These attributes cover specific criteria organized in relation to scope, platform, map, and analysis. The Framework section (Table 1) provides information related to the structure of the sites and their maps. The Functionality section (Table 2) refers to the usability of the tool in terms of tasks that may be performed and the resulting extracted information.

3 Overview of Tools

3.1 Global Solar Atlas

The Global Solar Atlas (https://globalsolaratlas.info/) was created in 2017 by the World Bank Group (WBG) with funding from the Energy Sector Management Assistance Program (ESMAP), to support the development of solar resources in its client developing countries, although the tool covers all countries for which solar resource data are available. It provides long-term averages of solar resources (global, diffuse, and direct normal) for early-stage project management, which includes prospecting and preliminary assessment. The WBG stores some of its data and analytics at https://energydata.info/, an open data repository supporting the energy sector.

The global provider of solar data for the application is Solargis, a specialist company based in Europe that disseminates solar data and consultancy services. Data was amassed as far back as 1994 (Africa and Europe), 1999 (the Americas, Middle East, and Russia), and 2007 (China and Australia) and goes through 2015 at temporal resolutions ranging 10-30 minutes. Three modeling methodologies are used in the creation of continuous data:

1. Solar Radiation Model: This method uses clear-sky irradiance modeling, considers numerous atmospheric attributes, and combines these with meteorological satellite data to determine direct, diffuse, and global irradiance;
2. Air Temperature Model: The Global Solar Atlas uses time-series air temperature data from global models processed down to local scales. Next to irradiance, temperature is the most important aspect contributing to solar photovoltaic (PV) technology performance;
3. PV Power Simulation Model: This model takes the two model methods above and calculates potentials between small-, medium-, and large-scale systems. A theoretical potential, in this case defined by Solargis as completely ideal conditions, is also considered in the comparison.

Data resolutions in the Global Solar Atlas are in the 3-7 kilometer range then downscaled to 1 kilometer. Elevation data and terrain shading are used in the downscaling algorithm process. The solar resource model is validated by using data from over 200 sites worldwide under strict quality control measures. The most recent updates for the website in 2018 included new static maps for 145 countries (available for download) and a future release scheduled for mid-2019 expects updated solar resource data (incorporating two additional years of satellite data and modeling improvements), increased map resolution (further downscaled to 250m), and 24 x 12 data (hourly-monthly) that will show the average monthly solar resource potential for each hour of the day.

The Global Solar Atlas displays a world map with one of five different solar energy inputs or outputs: PV electricity output (the Solargis Theoretical Potential mentioned above), global horizontal irradiation, direct normal irradiation, diffuse horizontal irradiation, and global tilted irradiation (Figure 2). In addition, one map displays optimal PV equipment installation angles. Lastly, three reference maps are also included, although only one map at a time may be displayed due to the continuous data. Data is available for download as PNG, TIFF, AAIGRID, or GEOTIFF file types.

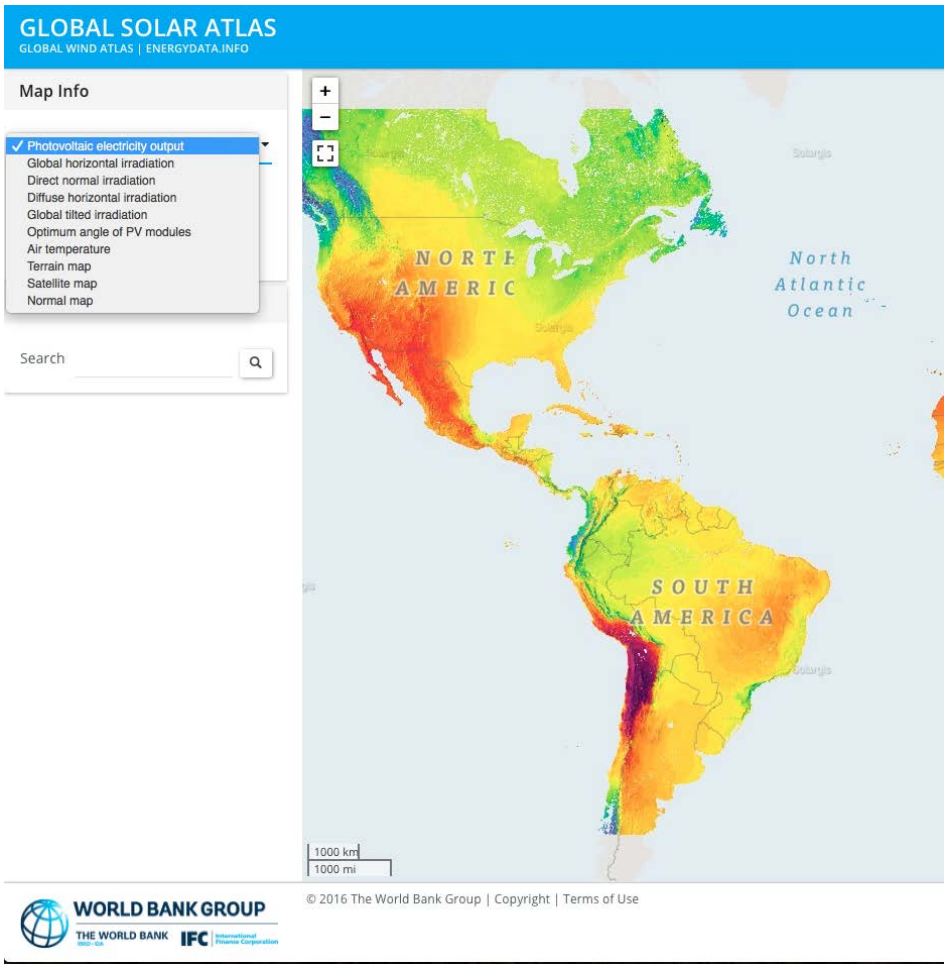

Figure 2. Global Solar Atlas homepage with selectable attributes displayed at left

Image from World Bank Group 2019

Users can click the map to find a location's attributes, displaying a sidebar of information and leaving the map itself unimpeded (Figure 3). Displayed attributes can be switched between metric or English units and daily or annual data with radio buttons. Zoom and pan features exist.

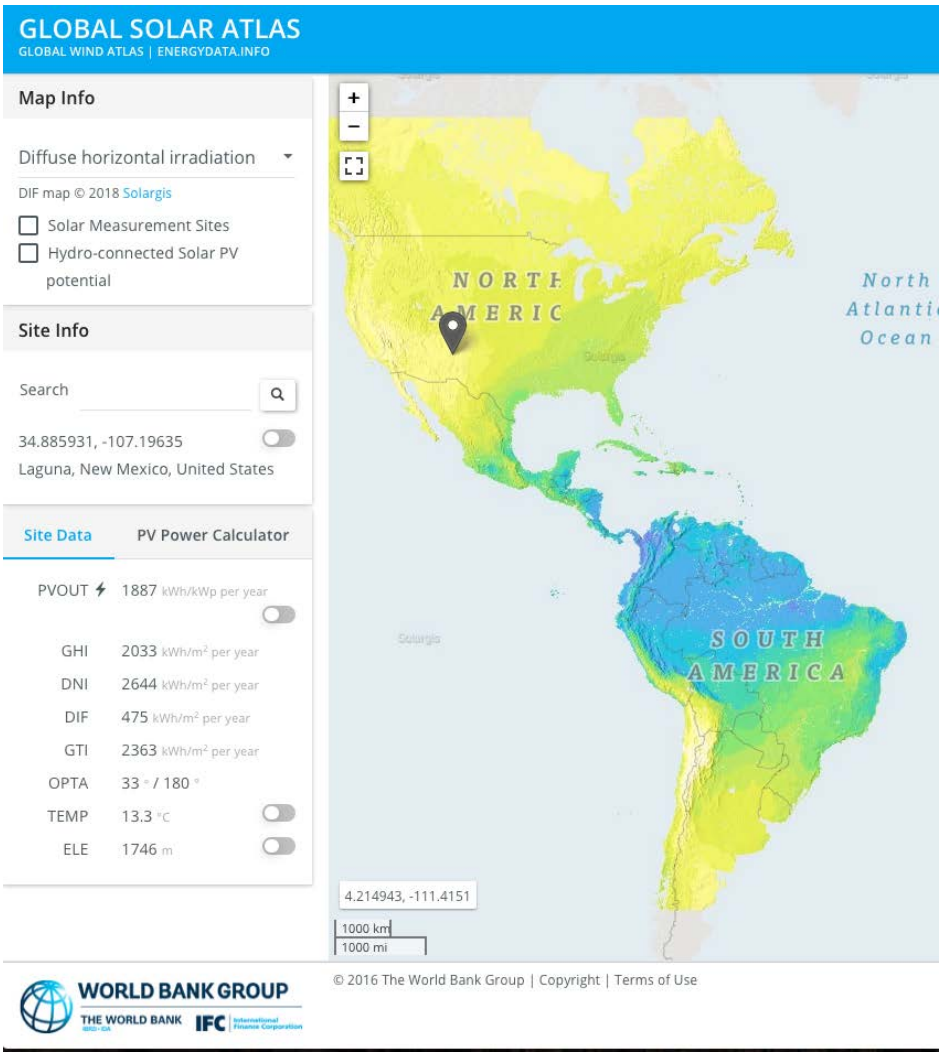

Figure 3. The Global Solar Atlas showing diffuse horizontal radiation data for a point in the southwestern United States.

Image from World Bank Group 2019

Information in page- and poster-sized maps can be downloaded for seven regions or 145 countries (Figure 4), as well as GIS data in raster form. The interface is intuitive.

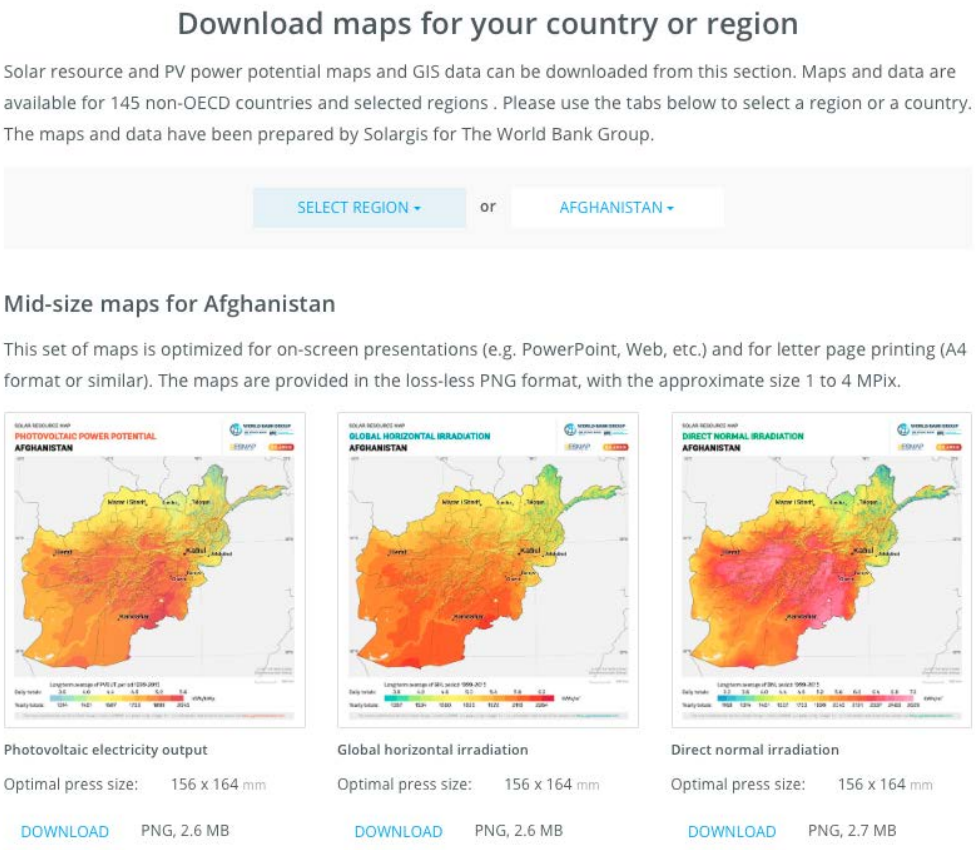

Figure 4. Sample Global Solar Atlas maps available for download

Image from World Bank Group 2019

3.2 Global Wind Atlas

Similar to the Global Solar Atlas, the Global Wind Atlas 2.0 (https://globalwindatlas.info/) was developed by the WBG and the Technical University of Denmark, with funding from ESMAP and data stored at EnergyData. It uses mesoscale modeling data generated by the company Vortex, who were contracted by ESMAP as part of the initiative. Other partners in developing previous versions of the Global Wind Atlas include the Clean Energy Solutions Center, Energypedia, and OpenEI.

Data for the Global Wind Atlas site was drawn from the European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis (ERA5) modeling sets at a mesoscale 9-kilometer resolution, an update from earlier versions using large-scale atmospheric data. From the mesoscale 9-kilometer resolution, microscale modeling reduces this to 250 meters, with wind readings at elevations of 50, 100, and 200 meters representing wind turbine hub heights. Microscale modeling considers the topography, orography (the mountainous nature of the terrain), surface roughness, and obstacles to determine local wind speeds.

The Global Wind Atlas was updated in fall 2018 with expanded functionality and features. Selectable attributes now include wind capacity factors of International Electrotechnical Commission (IEC) Class I-III on the Wind Energy Layers drop-down menu of the Wind Power

Density tab (Figure 5). Wind power density is a measure of the wind resource, with higher densities indicating greater resources. Capacity factors indicate nominal resource potential, the baseline described by the potential pyramid (Figure 1).

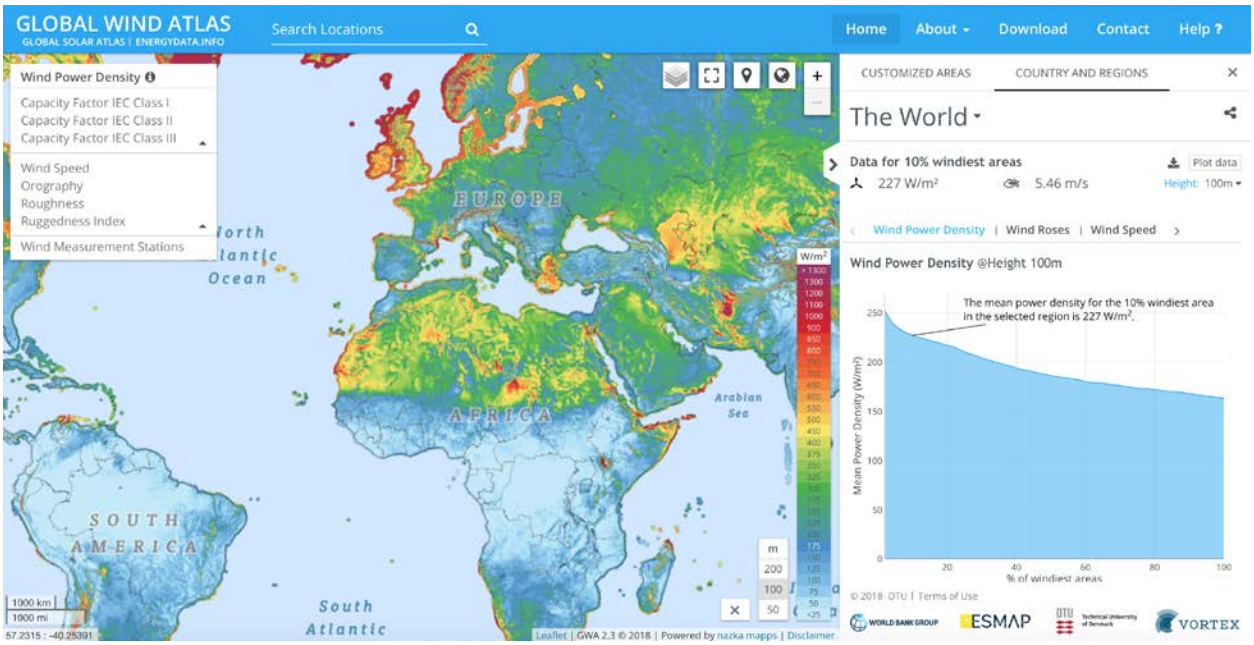

Figure 5. Global Wind Atlas homepage displaying attributes at left, charts and graphs at right.

Image from World Bank Group 2019

Wind classes are defined by the IEC, factoring in wind speed, extreme gusts, and turbulence (LM Wind Power 2019). Class I wind is considered high, with an annual average wind speed of 10 meters per second, down to Class IV, very low wind, with an average of 6 meters per second. The Global Wind Atlas allows for selection of Classes I-III at elevations of 50, 100, and 200 meters representing common turbine hub heights, and displays the percentage value for a selected combination of these attributes.

In addition to wind power density, the Global Wind Atlas allows the user to display explanatory layers, attributes used in the modeling that downscale regional data to local results. These layers include simplified wind speed, orography, roughness of the earth's surface (cities and forests increase roughness over bare earth), and a ruggedness index (a measure of steepness). For areas of great steepness, such as mountain ranges, the accuracy of wind resource data is reduced.

Custom areas of interest may be selected on the map by selecting a point, rectangle, or polygon tool on the right of the map (Figure 6). Alternatively, countries may be selected from a drop-down menu or a subset region within that country, and the map will zoom to the selection. Once selected, charts and graphs of data for the region are displayed. One particularly useful chart is the wind rose, indicating wind direction frequencies by percentage.

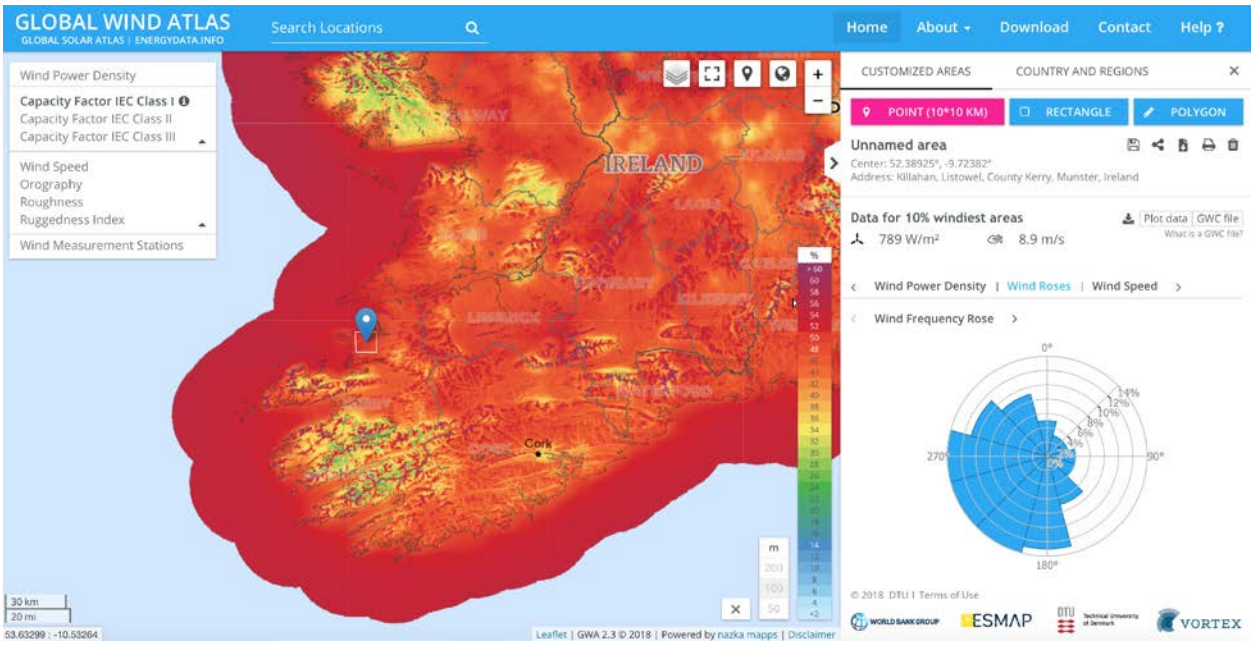

Figure 6. A custom point in the Global Wind Atlas displaying Capacity Factor Class I. Countries and regions may also be selected from the tab at the top of the data pane.

Image from World Bank Group 2019

User-defined areas may be downloaded as GIS data or PDF maps from the data pane to the right of the application, or countries and regions can be selected under the Download tab (Figure 7). GIS data may be downloaded as JSON and CSV data files.

A further update to the Global Wind Atlas (Version 3.x) is planned for mid-2019, and will include a revised modeling output using mesoscale data provided by Vortex at 3-km resolution, generated from the latest ERA5 data set from ECMWF. Microscale modeling by the Technical University of Denmark will recompute the resolution to 250-m, and several new features will be launched—including 24 x 12 data to match the Global Solar Atlas.

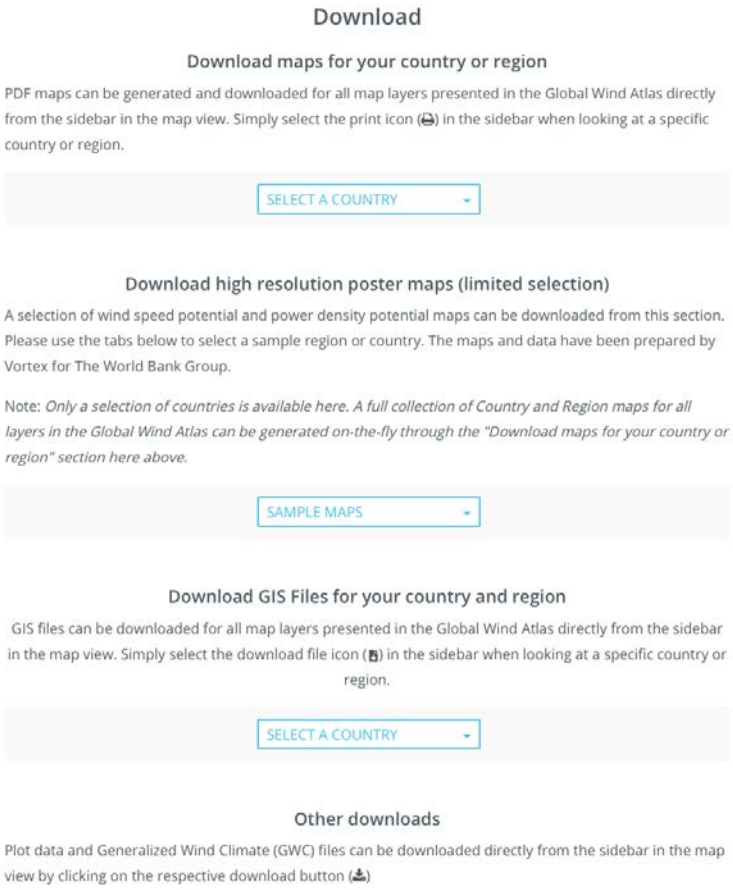

Figure 7. Selected maps and data from the Global Wind Atlas are available for download.

Image from World Bank Group 2019

3.3 MapRE

MapRE (http://mapre.lbl.gov/) was developed by the Lawrence Berkeley National Laboratory and went live in September 2015 as a data link for a technical workshop held in Nairobi, Kenya. The work culminated in a paper published March 27, 2017 (Wu et al. 2017). The research found great potential for wind and solar applications in eastern and southern Africa that could easily supply many more times than their energy demand, be cost-effective and competitive over conventional power plants, and potentially benefit large regions through international energy trade.

MapRE contains data sets for India and the African countries indicated in Figure 8. Sample maps display key RE results for solar and wind, including global horizontal irradiance, direct irradiance, and wind power density. Free registration is required to access the website's information. Once registered, users can access data sets for RE studies in wind and solar for the countries indicated. Both PDFs and geospatial data for the select countries are available for download, as well as comprehensive charts and databases with RE information. Metadata is also available for the geospatial data.

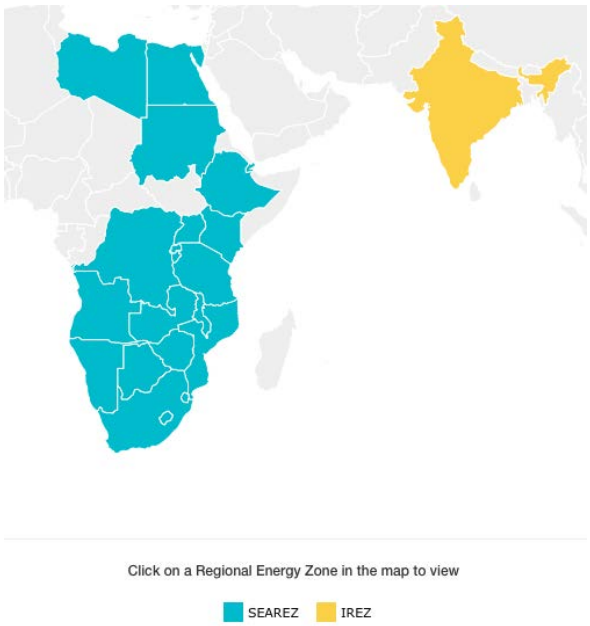

Figure 8. MapRE regions of study

Image from Lawrence Berkeley National Laboratory 2019

The interface for analysis is distinguished from other websites in this report as it is not a web application per se, but instead Python programming code, available as a download but not as a web interface (Figure 9). The code was used for the specific regions mentioned for the conference; however, documentation indicated the code is functional for any area with geospatial data. When adapted for different regions, the code has the capacity to perform exclusion analysis and resource potential estimation. It is noted that the code was intended for use with ArcGIS 10.x, an application requiring licensing. Due to the lack of a web interface to manipulate data, MapRE stands apart from the other sites reviewed, requiring programming knowledge and specific applications to run. Aside from a few updates to the code in 2019, the data and site have remained static as well. MapRE is significant, however, as it has enabled progress in the development of analysis techniques used in emerging web applications for RE.

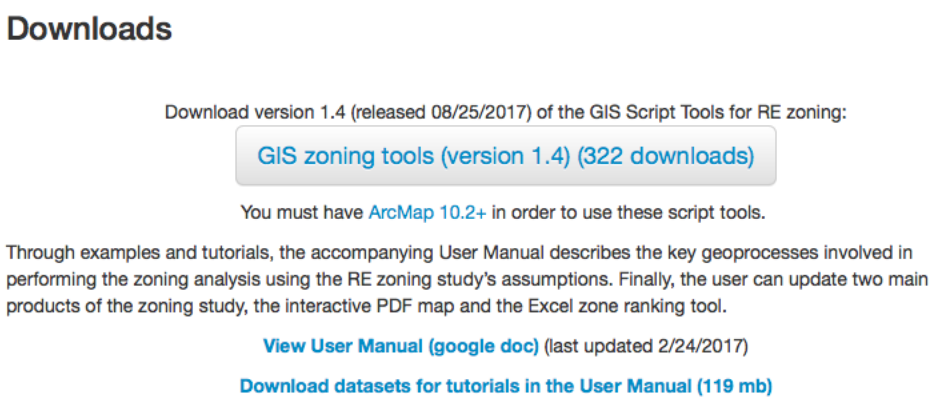

Figure 9. The MapRE zoning tools for ArcGIS are available for download.

Image from Lawrence Berkeley National Laboratory 2019

3.4 Photovoltaic Geographical Information System

PVGIS (http://re.jrc.ec.europa.eu/pvg_tools/en/tools.html#TMY) was developed by the European Commission Joint Research Centre in Italy to research and disseminate solar resource data and PV performance studies. While the web application is the most visible output, the Joint Research Centre does significant work in other studies, including improvements in estimates and validation and collaboration with many RE research groups. For PV, the Centre has conducted pioneering studies and created models examining PV performance over large regions of the Earth. PVGIS was the precursor to Solargis (the underlying data set to the Global Solar Atlas above) which replaced it, and thus has not had any recent updates.

PVGIS's initial base map is from OpenStreetMap and may be changed to one of several satellite or terrain options. As the title suggests, the application focuses on solar energy resources worldwide and holds a wealth of information regarding all aspects of solar data. Data includes attributes such as global and direct irradiation data in monthly, daily, and hourly temporal resolutions, on- and off-grid PV performance, and PV performance tracking. Several different PV databases with hourly temporal resolutions are available for selection, including:

- Climate Modeling Satellite Application Facility (CMSAF): Europe, Africa 2005-2016; spatial resolution 1.5 arc-minutes
- Surface Solar Radiation Data Set-Heliosat (SARAH): Europe, Africa, Asia, South America 2005-2016; 3 arc-minutes
- National Solar Radiation Database (NSRDB): North and South America 2005-2015; 2.4 arc-minutes (NREL)
- European Centre for Medium-Range Weather Forecasts Re-Analysis (ERA5): Worldwide re-analysis model 2010-2016; 0.28 degrees lat/long.

PVGIS is a data-driven site, and visualizations are limited. The map is solely used for determining location, and various charts and graphs are instead used to display selected information (Figure 10). When an attribute is chosen to map, such as monthly direct normal irradiation, a graph appears in the lower part of the window with the information. The map itself remains unchanged and is not used to display visualizations like the other web applications.

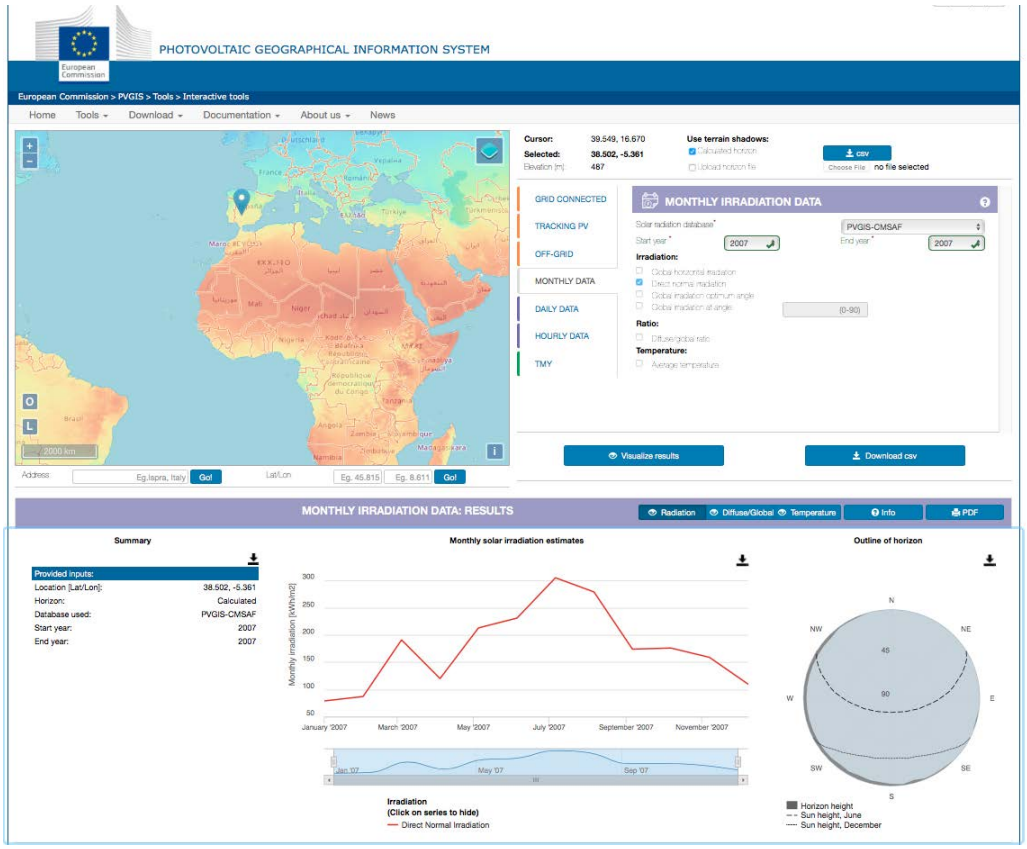

Figure 10. PVGIS solar data is displayed in charts and graphs for selected areas; the map remains unchanged.

Image from European Commission Joint Research Centre 2017

Data is available for download as a CSV file for selected areas, or links are also provided for the NSRDB developed by NREL. Ready-made static maps are available as a PDF or PNG for select data in European and African countries (Figure 11). It should be emphasized that the strength of the site lies in its extensive available data and plotting, with a lesser focus on visualization. The site contains a user manual that describes major features.

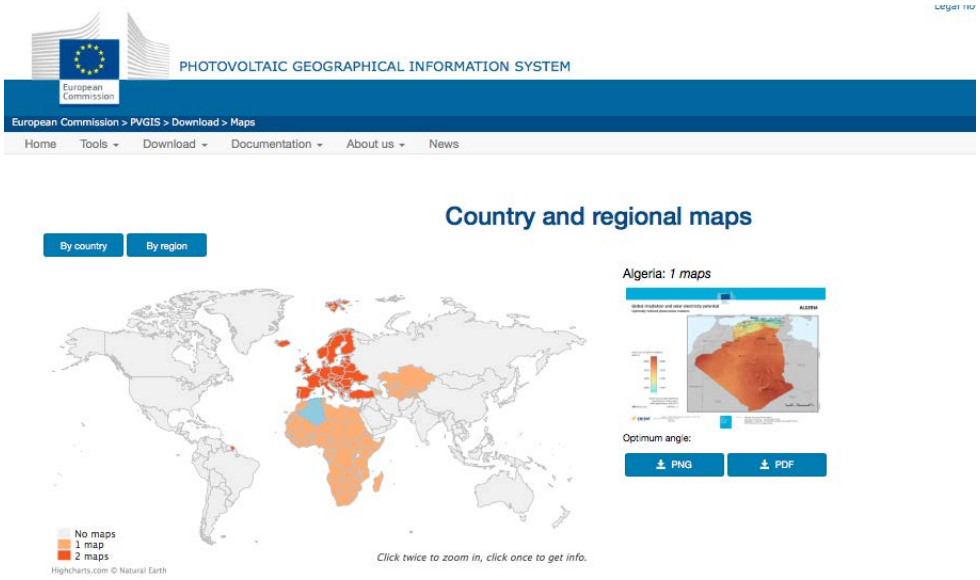

Figure 11. Select PVGIS data for indicated countries is available in ready-made maps.

Image from European Commission Joint Research Centre 2017

3.5 IRENA Global Atlas

IRENA is an intergovernmental organization comprising 170 member states supporting RE development. In addition to the Global Atlas, IRENA also works on many studies about costs and benefits of renewables across the globe and aims to be a principal platform and repository for RE information, studies, and data. This information allows member states to make informed RE decisions.

The main page of the IRENA Global Atlas has a dashboard-type interface with buttons to filter published content by maps, tools, and the five main RE sources: wind, solar, hydropower, geothermal and bioenergy (Figure 12). A drop-down menu can be used to sort the maps by country. After selecting a sample map, the interface is very GIS-oriented, where different layers can be ordered as needed and turned on and off; the legend is visible and effective (Figure 13). Metadata is robust, indicating sourcing and attribution requirements, though it is not necessarily consistent between layers, especially between different source organizations (Figure 14).

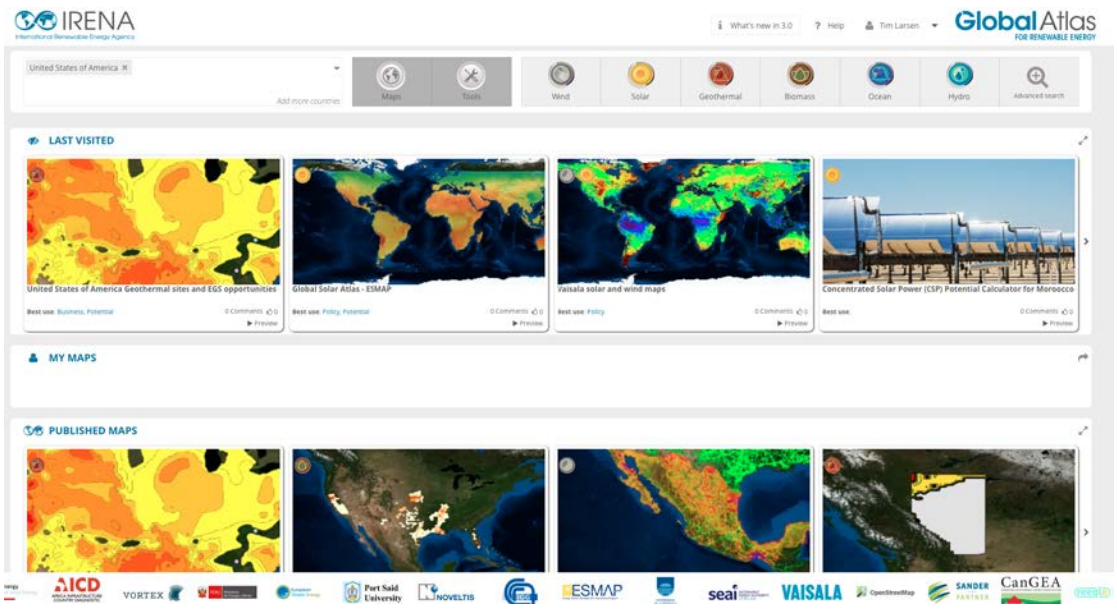

Figure 12. IRENA homepage, with sample maps produced by users. Radio buttons at the top filter results by keywords.

Image from IRENA 2019

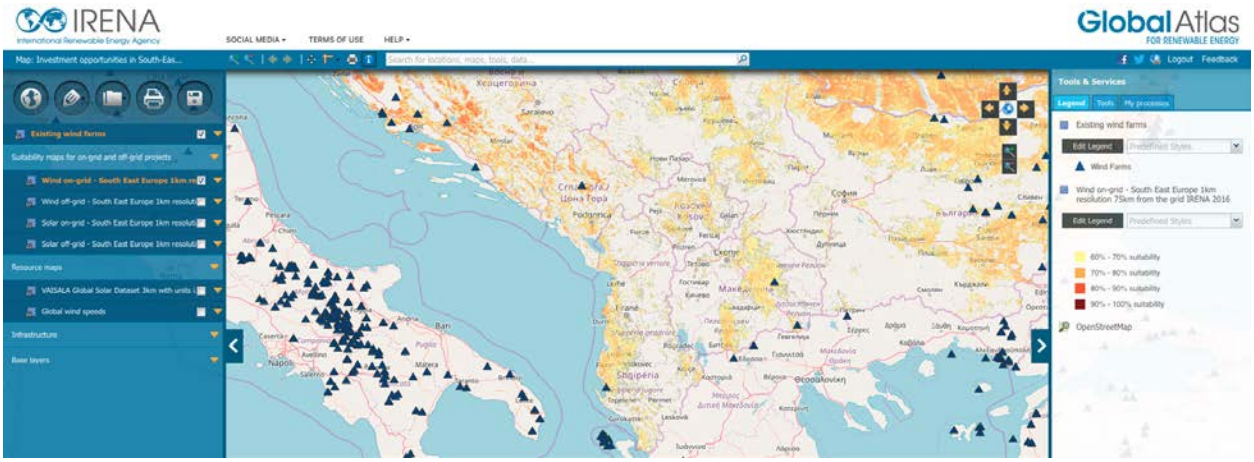

Figure 13. IRENA GIS interface for published maps.

Image from IRENA 2019

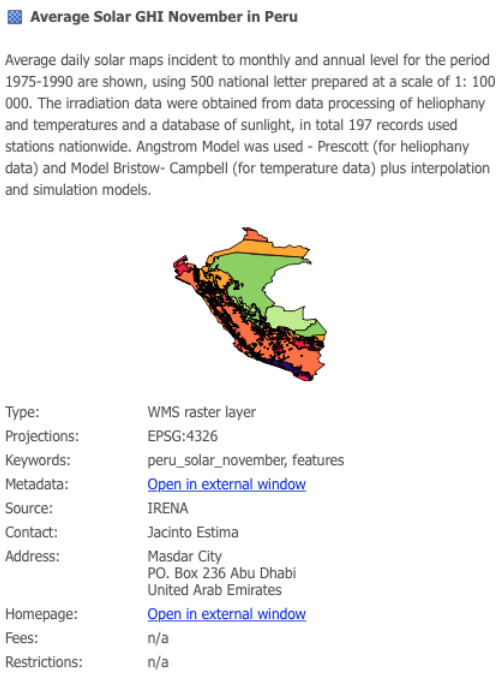

Figure 14. Sample IRENA metadata

Image from IRENA 2019

About a dozen sample maps visualizing various RE layers and tools are available on the homepage. Creating an original map is also possible, but further guidance on the process proved difficult to find. One approach is using an existing tool to create a map, then adding supplemental layers. The IRENA catalog includes many GIS layers (1,690 at the time of this count) at the country to international level; however, the user must be aware of the desired data and use effective search techniques, as the file organization does not always follow a standard convention (Figure 15). In addition, users must be aware of possible inconsistencies in relevancy and accuracy of the data. This was the only site reviewed where the option to upload a layer as a GML/KML or GPX from a web address readily existed, and this is likely where the disparity in file naming conventions stems from. IRENA has its own YouTube channel for training purposes and a Global Atlas zoning service to assist member countries in resource planning.

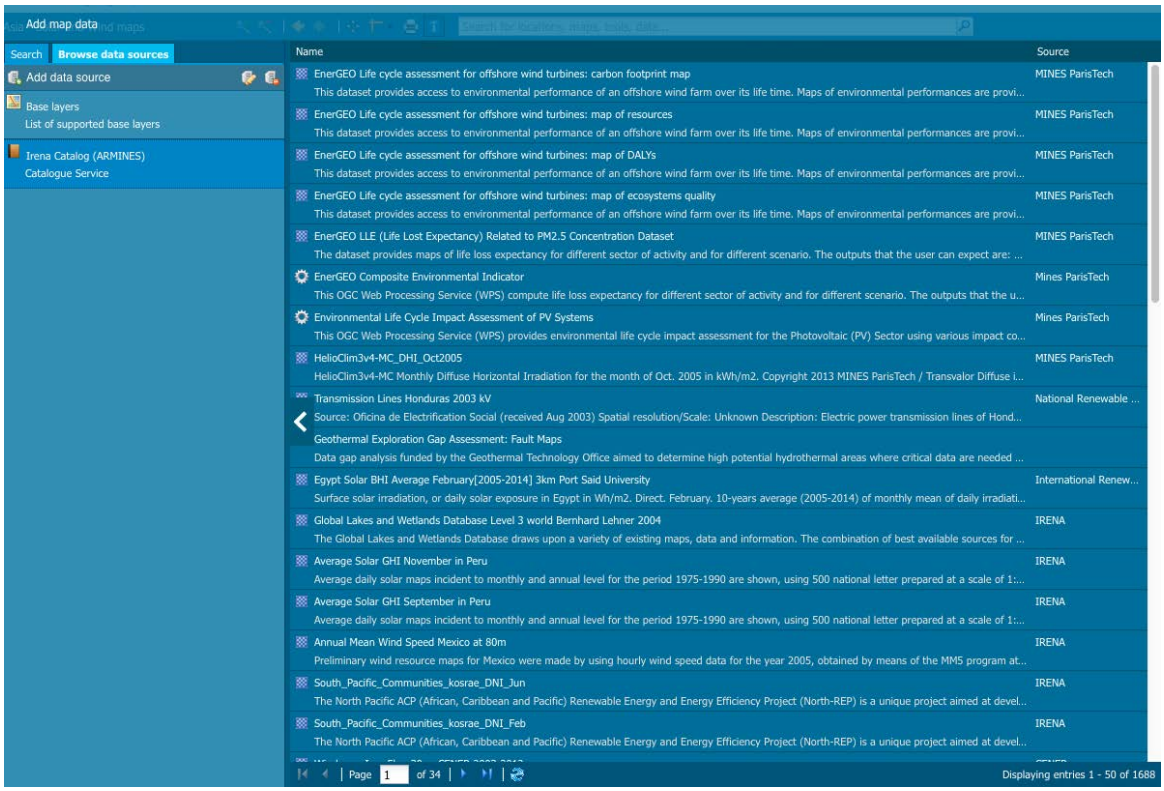

Figure 15. Numerous files have been uploaded to IRENA, but users need effective search queries.

Image from IRENA 2019

3.6 RE Explorer

NREL's RE Data Explorer is the flagship interactive geospatial analysis tool of the organization's RE Explorer, a collection of data and tools for analysts. RE Data Explorers are available for 12 countries and regions (Figure 16), and the data sets contain information on wind and solar potentials, along with hydropower, geothermal, biomass, and wave, where applicable (Figure 17). Administrative layers add details like political boundaries, protected areas, and power plant locations and types. Natural feature layers include waterbodies and wetlands, volcanic areas, elevation, and land use. Layers can be easily switched on and off and ordered as desired in the Legend pane (Figure 18). Layer transparencies can also be applied in the legend. Many layers can be downloaded directly from the map as a CSV, shapefile, KML, or GeoJSON. Data uploads are considered on a case-by-case basis to be included in the interactive application or the static RE Data Catalog. User guides, videos, and fact sheets are available.

Figure 16. Countries currently available for RE Data Explorer

Image from NREL 2019

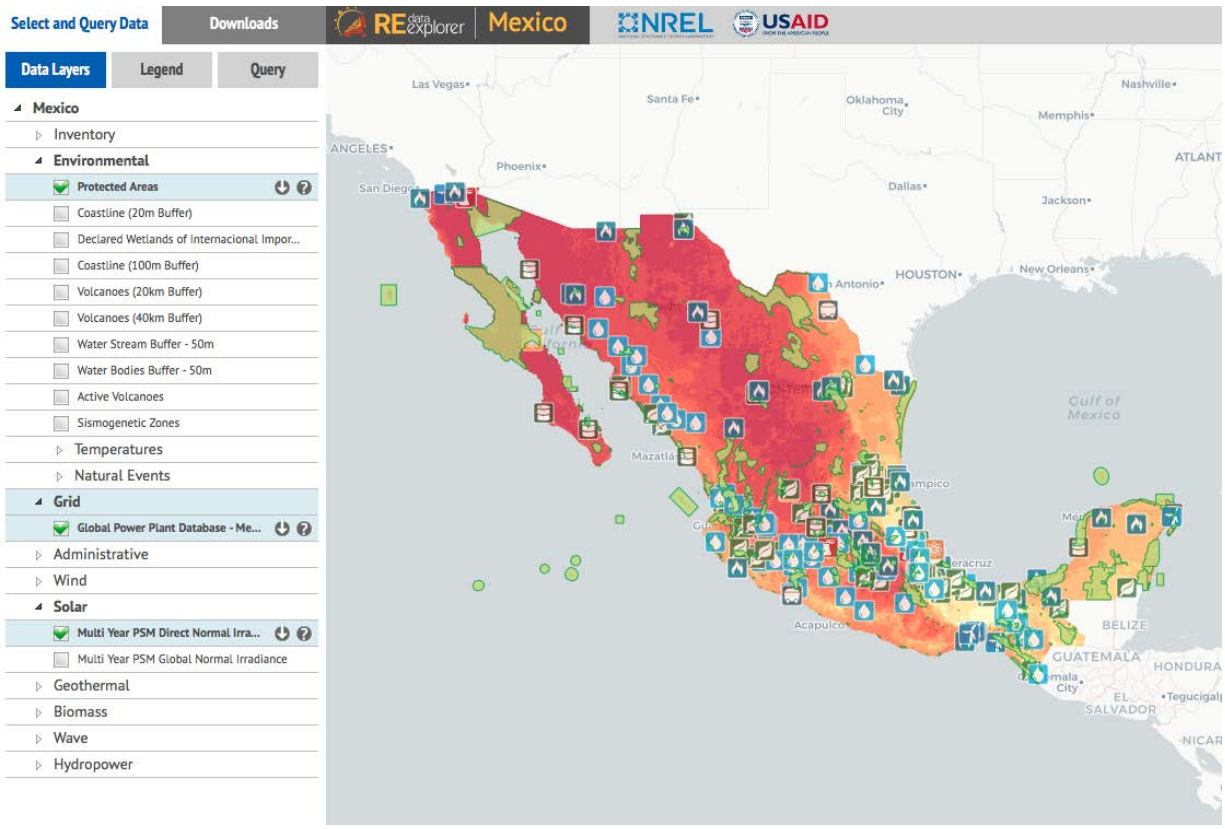

Figure 17. RE Data Explorer selectable and downloadable attributes

Image from NREL 2019

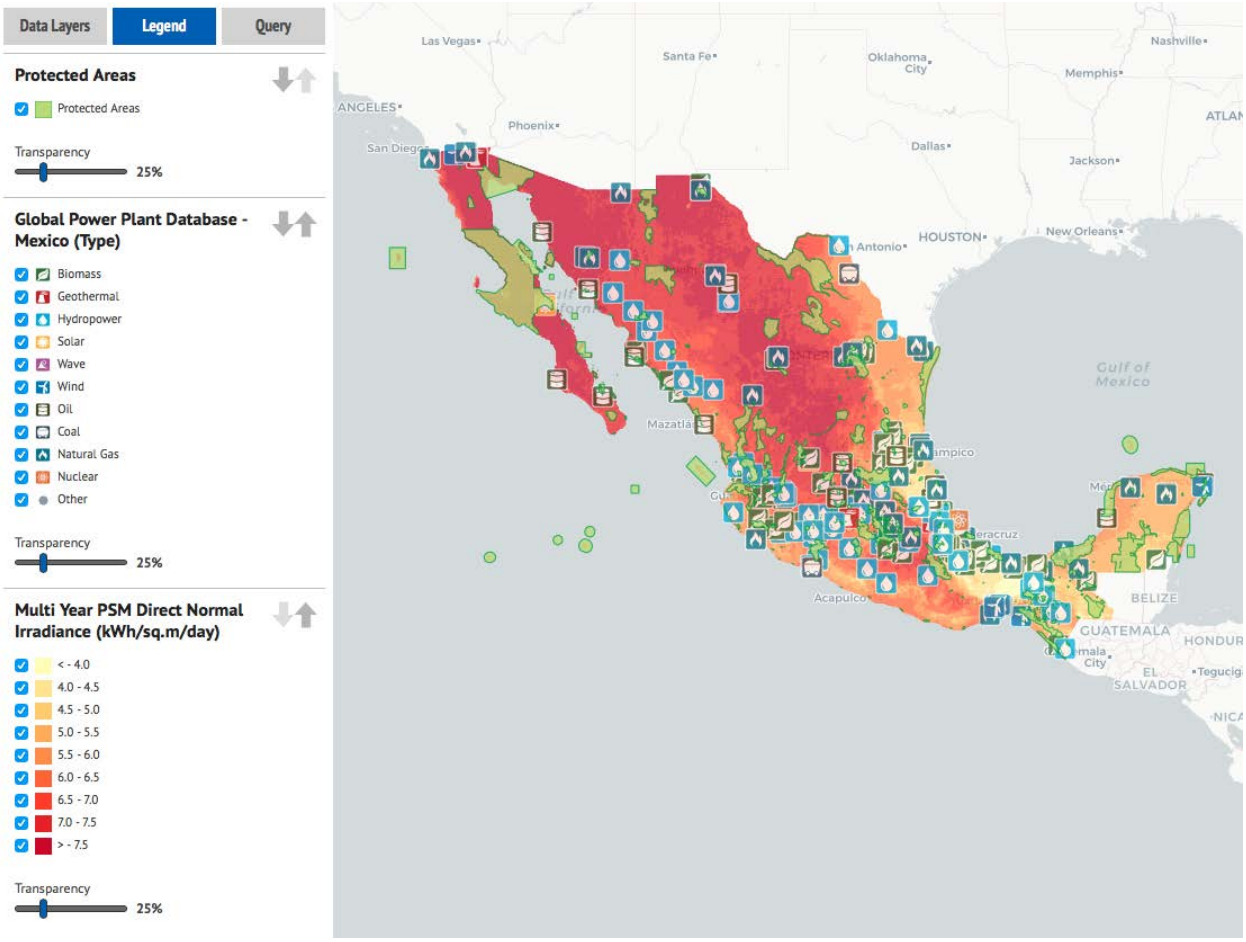

Figure 18. RE Data Explorer layers may be ordered and transparencies adjusted in the Legend pane.

Image from NREL 2019

The Technical Potential Tool is also available for some countries to display the viability of various RE sources based on numerous selected attributes (Figure 19 and Figure 20). Exclusions and limits can be applied to these attributes of a technology, creating different scenarios. The different exclusions are as follows:

- Limit Results by Resource: Finding areas of solar or wind power above a certain unit threshold;
- Limit Results by Power Density: Representing the reasonable capacity of a unit of land;
- Limit Results by Proximity: Finding areas a certain distance close to or away from infrastructure;
- Exclude Protected Areas
- Exclude Results for Land Cover/Land Use: For land surfaces unfeasible for certain technologies
- Limit by Slope: Where topography precludes RE technology construction.

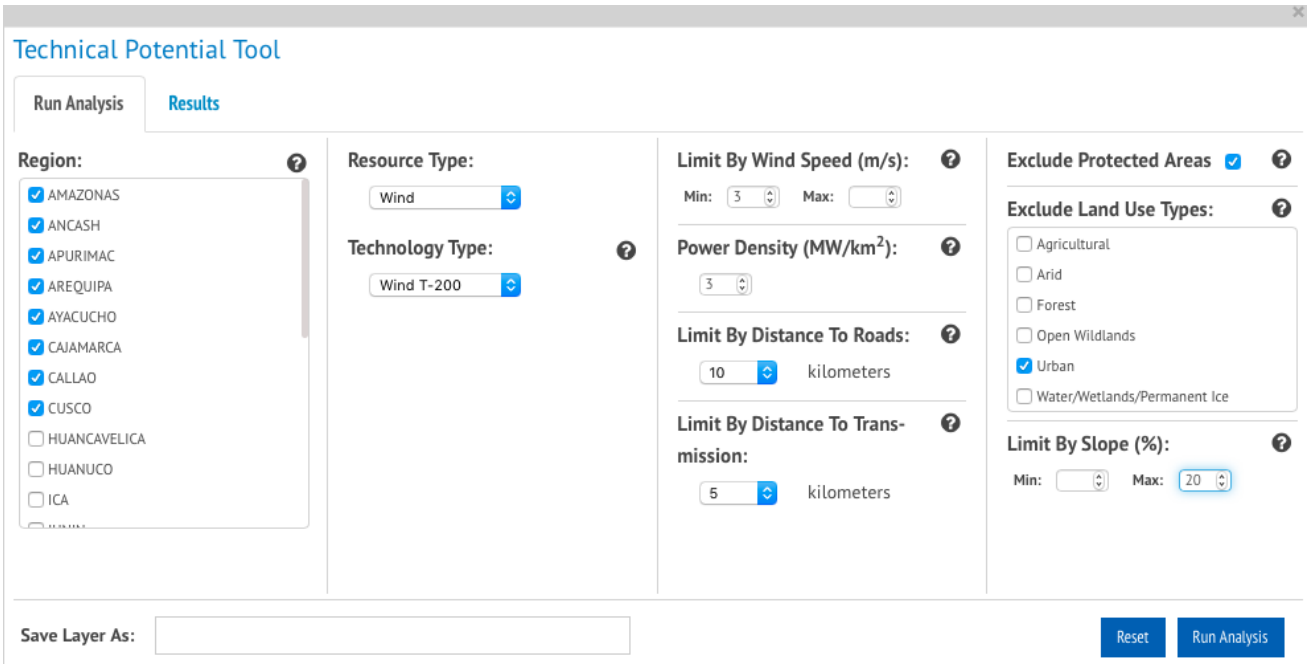

Figure 19. The RE Data Explorer Technical Potential Tool, available for some countries, allows users to define exclusions and constraints to inform site selection.

Image from NREL 2019

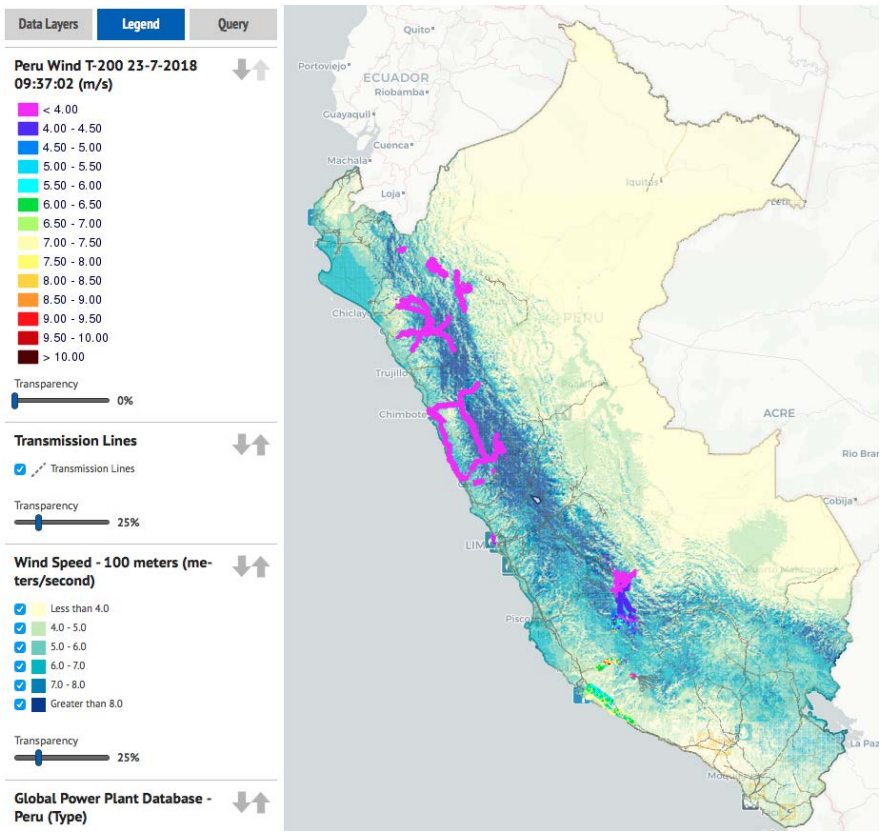

Figure 20. Sample results of the RE Data Explorer Technical Potential Tool.

Image from NREL 2019

For some regions, an economic potential tool is also available that begins to factor in the costs of development, operation, and maintenance of RE. Economic potential builds off technical potential, adding minimum revenue requirements for developing the resource through assumptions and outputs of generator and supply curve modeling, creating a levelized cost of energy (LCOE). LCOE is a metric by which energy systems can be standardized and compared. Through these means, a net value for the RE technology of an area can be determined and its economic potential met.

4 Discussion: Quantitative Results

Table 1. Frameworks of Web Tools

Framework:	RE Explorer	Global Atlas	Solar Atlas	Wind Atlas	PVGIS	Map RE
Scope						
Global	no	yes	yes	yes	no	no
Regional	limited[1]	yes	yes	yes	no	no
Country	yes[2]	yes	yes	yes	yes[1]	yes[1]
Platform						
Dynamic Map	yes	yes	yes	yes	yes	yes[2]
Static Maps	no[3]	no	yes[1]	yes[1]	yes[2]	yes
Online	yes	yes	yes	yes	yes	no
Registration Needed	no	yes[1]	no	no	no	yes[3]
GIS Data Download	yes[4]	varies[2]	yes[2]	yes[2]	yes[3]	yes[4]
Map						
Layering Ability	yes	yes	no	no	no	yes
Resolution, Wind	1km[a], 1.7km[b] 3km[c], 50km[d]	varies[3]	n/a	250m	n/a	500m
Resolution, Solar	1km[e], 4km[f], 10km[g]	varies[3]	1km	n/a	6km[a], 30km[b]	500m
Resolution, other	30km, 50km (offshore)[h]	varies[3]	n/a	n/a	n/a	n/a

Notes:

RE Explorer: 1. ASEAN: Assoc. of SE Asian Nations: Brunei Darussalam, Burma, Cambodia, Indonesia, Lao PDR, Malaysia, Philipines, Singapore, Thailand, Vietnam; Central Asia: Kazakhstan, Kyrgyz Republic, Tajikistan, Turkmenistan, Uzbekistan
2. Afghanistan, Bangladesh, Ghana, India, Kenya, Mexico, Nepal, Pakistan, Peru
3. Produced maps can be downloaded or printed with selected areas
4. File formats include csv, shp, kml, geoJSON
a. Most maps include 1km resolution, plus: b. Central Asia, India; c. Bangladesh, Mexico; d. Central Asia
e. Most maps include 1km resolution, except: f. Mexico, Peru; g. Central Asia
h. Kenya: 30km offshore wind; Mexico: 50km offshore wave

Global Atlas: 1. Sample maps available without registration; 2. Downloads indicated but not functional; 3. Dependent upon uploaded data

Solar Atlas: 1. Static maps available; 2. GeoTIFF and Arc/Info file formats

Wind Atlas: 1. Static maps available; 2. TIFF and geoJSON file formats

PVGIS: 1. Results for a single point; 2. Static maps of solar potential for Africa, Europe; 3. File formats csv and epw
a. Resolution for Europe, N. Africa; b. Global

MapRE: 1. Angola, Botswana, Burundi, DR Congo, Djibouti, Egypt, Ethiopia, India, Kenya, Lesotho, Libya, Malawi, Mozambique, Namibia, Rwanda, South Africa, Sudan, Swaziland, Tanzania, Uganda, Zambia, Zimbabwe
2. After download, tool requires third-party software; 3. Required to access site; 4. Excel supply curves, shp

The frameworks of quantitative attributes for all tools are summarized in Table 1. Frameworks are described in terms of scope, platform, and mapping ability. The scope provides the tool's geospatial range, the platform describes the amount of interaction the user has with the tool, and map describes the layering ability and general resolutions. Note for monothematic tools the resolutions were exact, and for RE Explorer and IRENA different maps may have different resolutions based on disparate data sets.

Table 2. Functionality of Web Tools

Functionality	RE Explorer	Global Atlas	Solar Atlas	Wind Atlas	PVGIS	Map RE
Resources[1]	W, S, G, B, H	W, S, G, B, H	S	W	S	W, S
Data Download	yes	no	yes	yes	yes	yes
Data Upload	yes[1]	yes[1]	no	no	no	no
Metadata Availability	yes[2]	yes	yes[1]	no	no	yes
Metadata Download	no	no	yes	no	no	yes
Analyses:						
Technical Potential Analysis[2]	R, D, P, S	yes[2]	R	R	R, T	R, D, P, S
Exclusion Analysis[3]	A, L	no	no	no	no	A, L
Economic Potential Analysis[4]	yes[3]	no[3]	no	no	yes	yes
Analysis Visualization Quality	high	moderate	high	high	low	high
User Guide/Training Resources	yes[4]	yes[4]	yes[2]	yes[1]	yes[1]	yes[1]

Notes on Functionality:

Resources: 1. W: wind, S: solar, G: geothermal, B: biofuels, H: hydro

Technical Potential Analysis: 2. Estimates of achievable energy based on availability, quality, system, topography, environmental, and land use constraints. Tool limits by R: resource, D: power density, P: proximity, S: slope; T: time

Exclusion Analysis: 3. Exclude A: protected areas, L: land cover/use

Economic Potential Analysis: 4. A subset of technical potential where RE development costs are compared to current or future energy options; currently available for India and Central Asia (pending)

Tool Notes:

RE Explorer: 1. Registration required; Data is added to RE Data Catalog pending review and possibly to tool; 2. Data descriptions within app; 3. available for India and Central Asia (pending); 4. Extensive documentation and videos

Global Atlas: 1. Data can be added via web address after new map is created 2. Dependent on uploaded data; 3. Econ Potential may exist, however searches were fruitless; 4. Documentation on 14 topics

Solar Atlas: 1. In downloaded data only; 2. One-page User Guide, FAQ, and other Resources

Wind Atlas: 1. Thorough documentation

PVGIS: 1. Thorough documentation including background on PV technologies and databases

MapRE: 1. Somewhat limited and site requires specialized knowledge

The functionality of the tools includes attributes of the data themselves, their metadata, and analysis potential for several fields (Table 2). All sites included data for display and analysis, and a few had functionality for data upload and download. Metadata, as is often the case, is inconsistent across the tools in forms of availability and structure. MapRE and RE Explorer had high levels of analysis available; however, the MapRE tool had to be downloaded and used on third-party software, while RE Explorer takes advantage of near-full functionality through its web interface.

Having discussed the strengths and weaknesses of the various web applications reviewed, it is helpful to revisit the energy potential pyramid to visualize where each has functionality in the hierarchy of resource development (Figure 21).

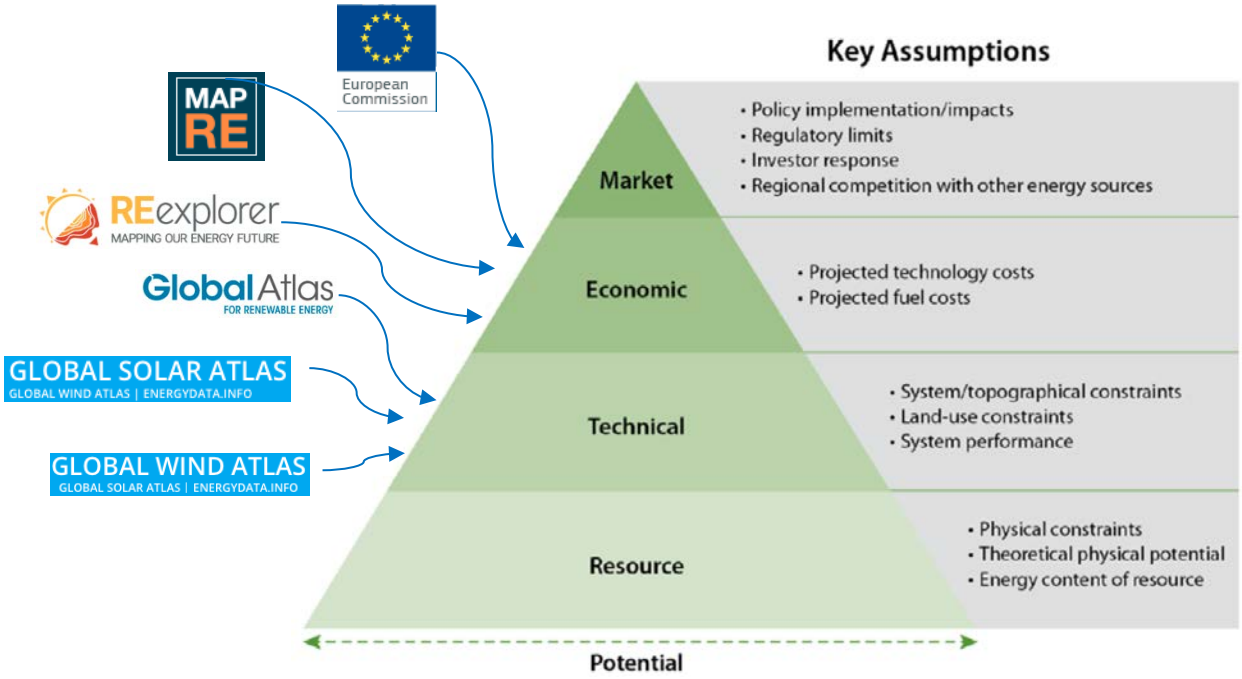

Figure 21. Energy potential pyramid showing where the six web applications lie in functionality.

Original image from Lopez et al. 2012

All applications cover information based on resource potential. For the Global Wind and Solar Atlases and the IRENA Global Atlas, technical potential is also included, but the sites do not go any further. RE Explorer, MapRE, and PVGIS all include forms of economic potential; however, each has limitations. MapRE, as discussed, is not a web application per se, and, as such, requires programming skills and access to ArcGIS to function. PVGIS is limited simply because it focuses solely on solar energy data. For RE Explorer, the application is limited to the locations that include the Economic Potential Tool (called the Cost of Energy Mapping Tool); however, work is ongoing to increase the tool's overall range and included countries.

5 Conclusion

Six GIS applications used to inform RE decisions were compared in relation to content and functionality. As noted and presented in Table 1 and Table 2, functionality varied significantly among the applications; however, all tools were determined to be useful in enabling RE decisions. It was also determined that further work should be done to understand the ways the tools are being used to inform RE development globally.

Appendix A. Climatescope 2017 Website Analysis

The Climatescope 2017 site (http://global-climatescope.org/en/) began in 2012, focusing on the energy use of Latin American and Caribbean countries, but it has since expanded to include over 70 developing nations, accounting for 32.5% of global gross domestic product (GDP) and 72.4% of population. The site is supported by the U.K. Department for International Development and Bloomberg New Energy Finance and was previously supported by the United States Agency for International Development (USAID). The energy data is displayed using its tools, though they are more akin to data display methods than analytic processes. The tools are as follows: Country Comparison, Off-Grid Data Hub, Clean Energy Investment, Capacity Generation, and Policies.

A.1 Country Comparison Tool

The Country Comparison Tool simply allows the user to select two countries to compare a host of information ranging from worldwide rankings and scores to GDP and RE statistics (Figure 22, Figure 23, and Figure 24).

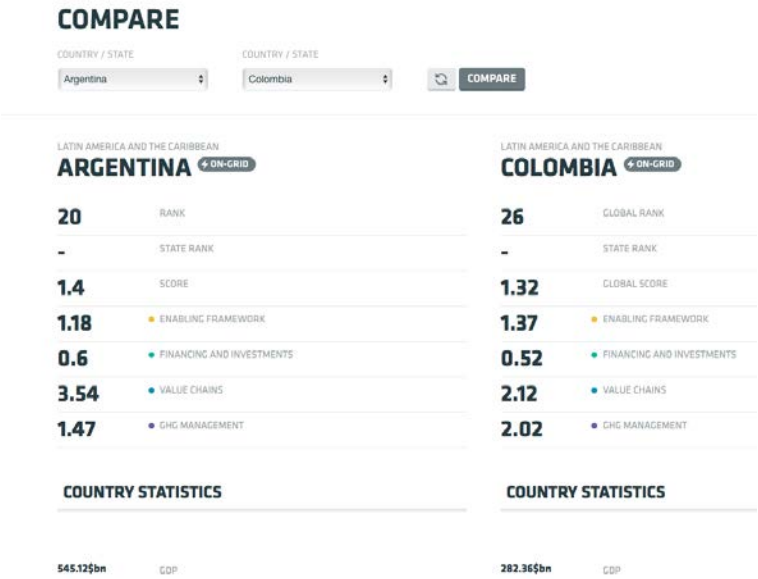

Figure 22. Two countries may be selected in Climatescope for comparison.

Image from BloombergNEF 2019

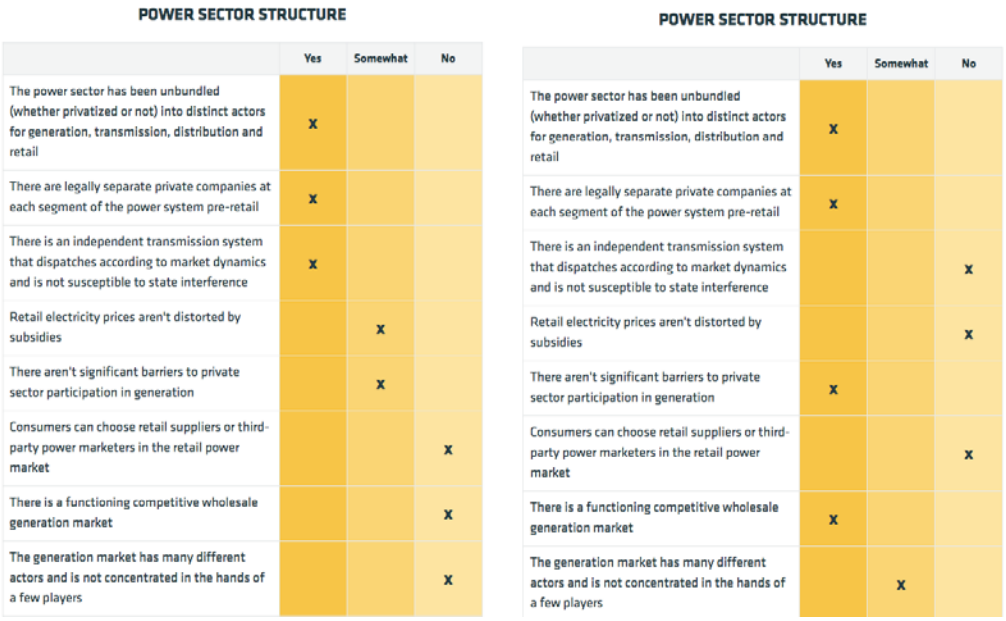

Figure 23. Attributes of power sector structure can also be compared in Climatescope.

Image from BloombergNEF 2019

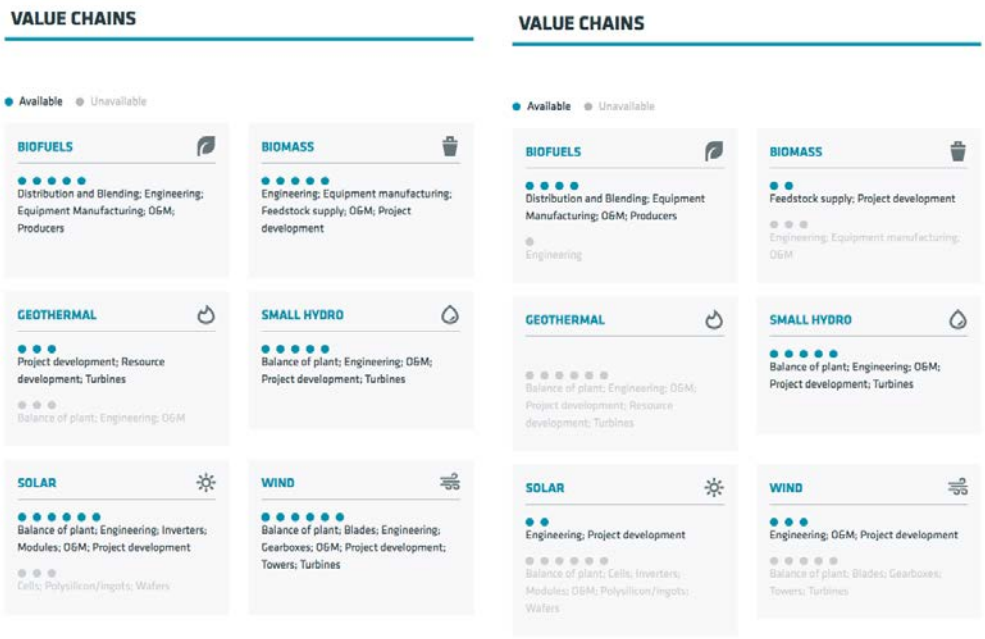

Figure 24. RE attributes are compared in Climatescope.

Image from BloombergNEF 2019

The tool is quite useful to compare two countries, and much of the data are industry standards. Defining the more ambiguous attributes on the page is one area for improvement, however. As it stands, detailed information is available on the Methodology page, but a quick definition of Rank and Score would be helpful, for example.

A.2 Off-Grid Data Hub Tool

The Off-Grid Data Hub Tool displays data or compares countries for attributes related to energy barriers, clean energy policies, energy frameworks, and power sector structure. It also graphs electricity pricing, fuel pricing, and access to electricity (Figure 25 and Figure 26).

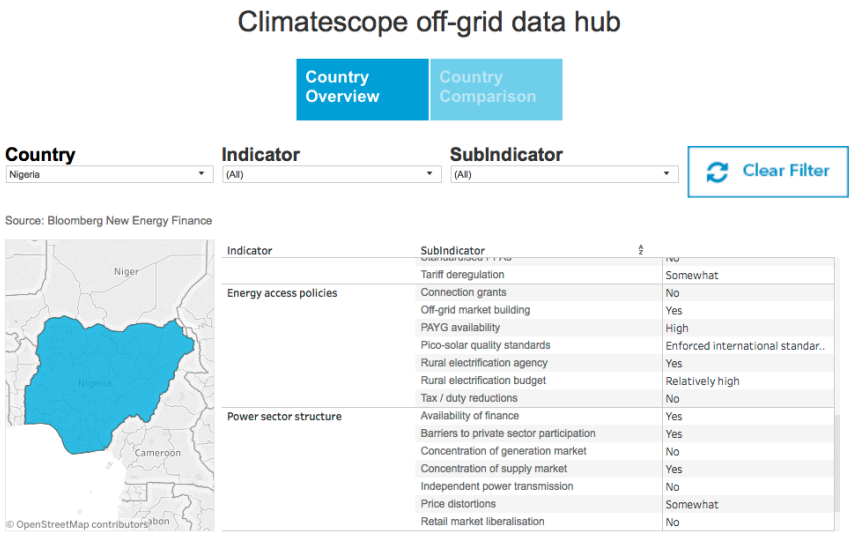

Figure 25. Climatescope displays availability of energy frameworks by country.

Image from BloombergNEF 2019

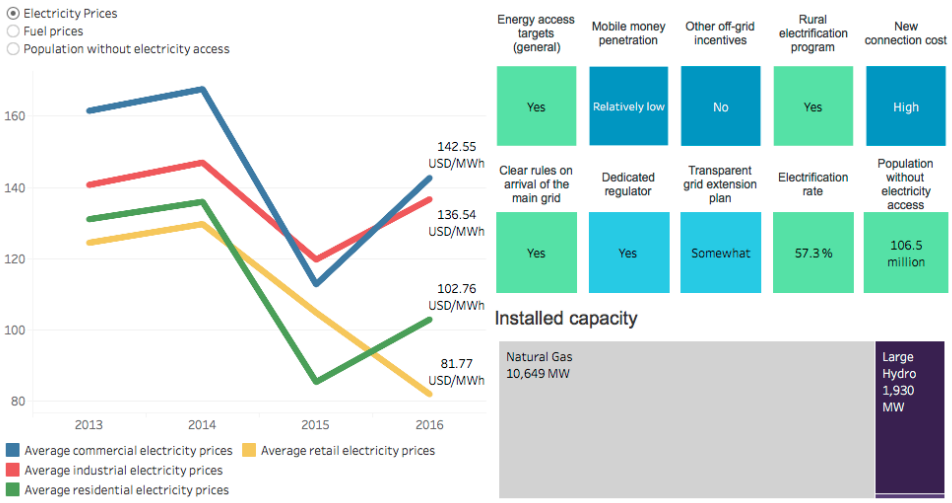

Figure 26. Climatescope's additional off-grid indicators

Image from BloombergNEF 2019

While industry standard statistics are included, more ambiguous data is included as well, such as ranking attributes as Somewhat or Relatively High.

A.3 Clean Energy Investment Tool

The Clean Energy Investment Tool displays RE investments for the last 10 years and can be filtered for countries or regions, as well as various attributes of the investors and recipients (Figure 27).

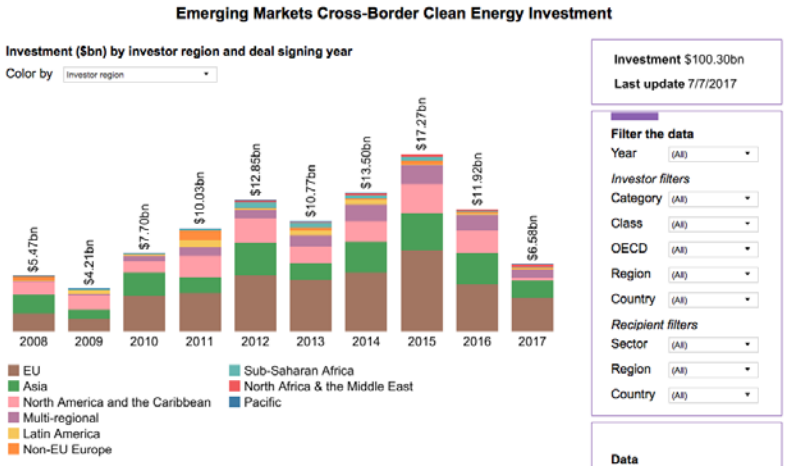

Figure 27. Climatescope investor data by region

Image from BloombergNEF 2019

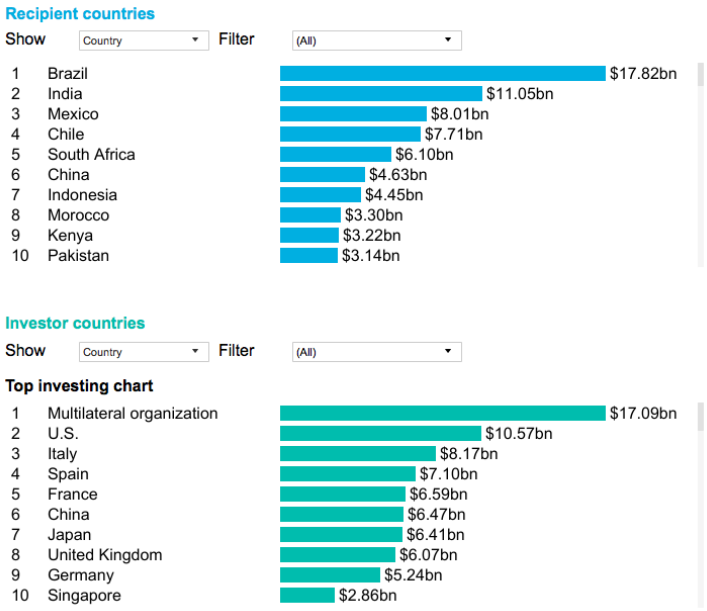

Figure 28. Recipient and investor countries

Image from BloombergNEF 2019

Figure 27 shows a powerful tool for doing general comparisons for numerous attributes, and the user can plainly see trends in investments over a span of years. The second graphs (Figure 28) display more absolute numbers for investor and recipient countries when displayed and filtered to the user's needs.

A.4 Capacity Generation Tool

The Capacity Generation Tool filters data to display installed capacity and generation by attributes like energy sector, country, or region (Figure 29).

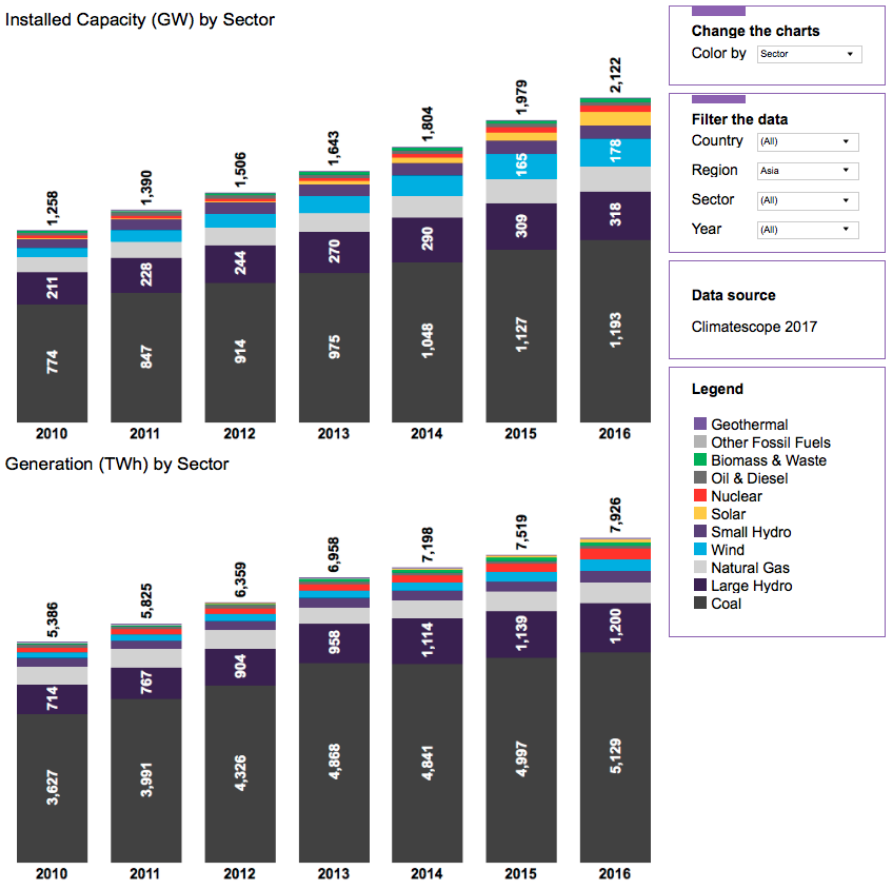

Figure 29. Examples of Climatescope capacities in Asia by sector and year

Image from BloombergNEF 2019

Once again, broad themes are easily compared, and the data for individual countries can be found by filtering the data down to individual attributes related to capacity.

A.5 Policies Tool

One of the more interesting tools available through Climatescope 2017, the Policies Tool, rounds up energy policies for the included countries. Results can be filtered by country, type, and status (Figure 30 and Figure 31).

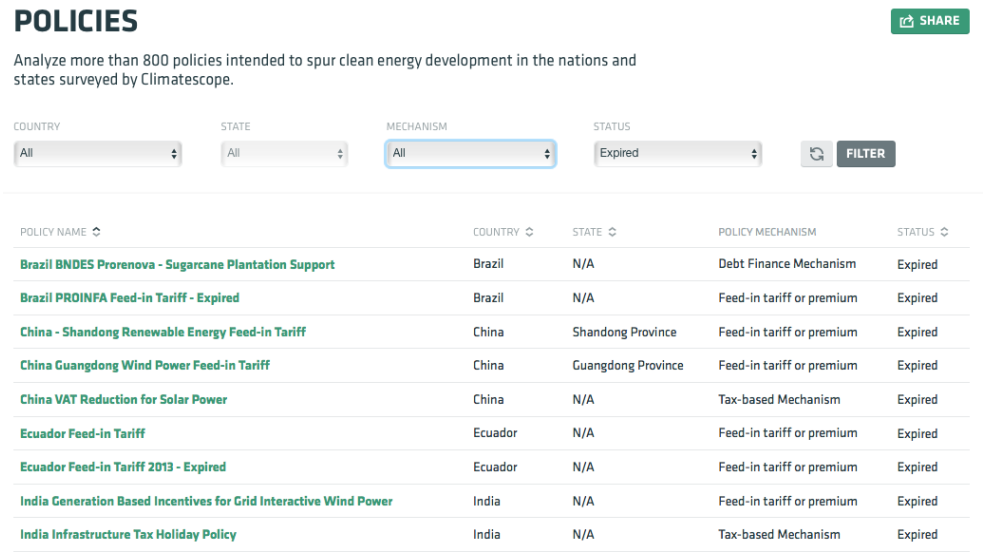

Figure 30. A sample of expired energy policies as displayed in Climatescope

Image from BloombergNEF 2019

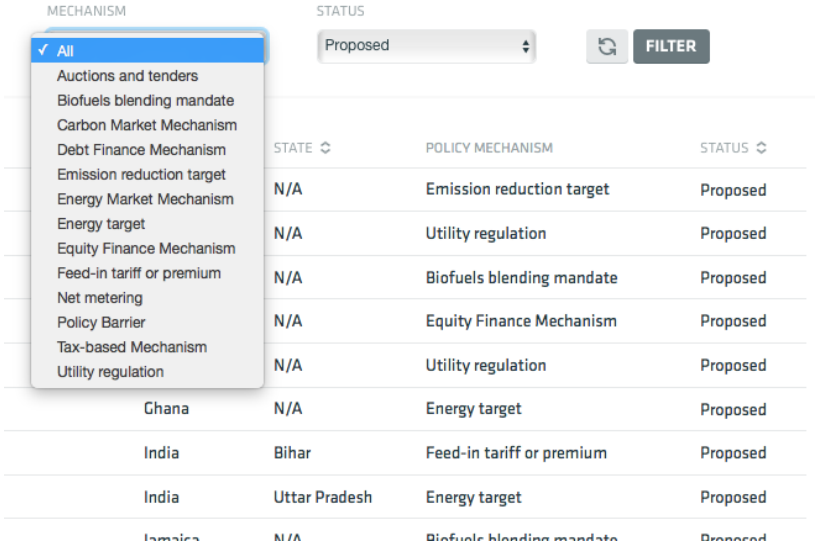

Figure 31. Different energy policy types contained in Climatescope

Image from BloombergNEF 2019

Detailed descriptions are accessed by clicking individual policies. While the filters are effective, filtering by time would also be helpful but is not available. Many of the policies, enacted or not, occurred at various times in the past, and it would likely be beneficial to be able to filter those results as desired.

Data is available for download within the tools and from a separate, more robust Download page. A Methodology page goes into detail on the process behind rating different countries, scoring approaches, and details of specific categories used in the different tools. All told, this appears to be a well-maintained site for energy information.

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www.re-explorer.org | www.nrel.gov/usaid-partnership

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NREL/TP-6A20-74233 | August 2019

Renewable Energy (RE) Explorer provides renewable energy data, geospatial analysis tools, and technical assistance to support data-driven renewable energy decision making. The RE Explorer was developed by the National Renewable Energy Laboratory and is supported by the U.S. Agency for International Development.

The USAID-NREL Partnership addresses critical challenges to scaling up advanced energy systems through global tools and technical assistance, including the Renewable Energy Data Explorer, Greening the Grid, the International Jobs and Economic Development Impacts tool, and the Resilient Energy Platform. More information can be found at: **www.nrel.gov/usaid-partnership**.

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