DELIVERABLE ONE: REPORT ON THE DST(S) FOR YOUR NATIONAL APPLICATIONS AREA

Climate Change Science Program

Uses and Limitations of Observations, Data, Forecasts, and Other Projections in Decision Support for Selected Sectors and Regions

Chapter 3. "Decision Support System for Assessing Hybrid Renewable Energy Systems"

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1. Introduction

The national application area addressed in this chapter is the deployment of renewable energy technologies. Renewable energy technologies are being used around the world to meet local energy loads, to supplement grid-wind electricity supply, to perform mechanical work such as water pumping, to provide fuels for transportation, to provide hot water for buildings, and to support heating and cooling requirements for building energy design. Numerous organizations and research institutions around the world have developed a variety of decision-support tools to address how these technologies might perform in a most cost-effective manner to address specific applications. This chapter will focus on one specific tool, known as the Micropower Optimization Model, Hybrid Optimization Model for Electric Renewables (HOMER), that has been under consistent development and improvement at the US Department of Energy's National Renewable Energy Laboratory and is used extensively around the world.

HOMER relies heavily on knowledge of the renewable energy resource available to the technologies being analyzed. Renewable energy resources, particularly for solar and wind technologies, are highly dependent on weather and climate phenomena, and are also driven by local microclimatic processes. Given the absence of a sufficiently dense ground network of reliable solar and wind observations, we must rely on validated numerical models, empirical knowledge of microscale weather characteristics, and collateral (indirect) observations derived from Earth observations, such as reanalysis data and satellite-borne remote sensors, to develop reliable knowledge of the geospatial characteristics and extent of these resources. Thus, the Decision Support System (DSS) described in this chapter includes HOMER as an end-use application and is described in the context of the renewable energy resource information required as input, as well as some intermediate steps that can be taken to organize these data, using Geographic Information Systems (GIS) software, to facilitate the application of HOMER.

2a. Description of the HOMER DSS

The HOMER DSS described in this chapter consists of three main components: (1) the renewable energy resource information required to estimate technology performance and operational characteristics, (2) (optional) organization of the resource data into a GIS framework so that the data can be easily imported into the decision support tool, and (3) NREL's Micropower Optimization Model known as HOMER, which ingests the renewable resource data for determining the optimal mix of power technologies for meeting specified load conditions at specified locations. This section describes each of these components separately. Although climate-based Earth observational data are primarily relevant only to the first component, some related Earth observation information could also be associated with the second and even the third component. Furthermore, it will be apparent that the first component is of major importance in the successful use of the HOMER DSS.

Although HOMER handles a number of power technologies, we will focus our attention in this chapter on solar and wind technologies and the resources required to run these technologies.

Solar and Wind Resource Assessments

The first component of the HOMER DSS is properly formatted, reliable renewable energy resource data. The significant data requirements for this component are time-dependent measurements of wind and solar resources, as well as Earth observational data and data from numerical models, to provide the necessary spatial information for these resources, which can vary significantly over relatively small distances due to local microclimatic effects. Because of this natural variability, it is necessary to examine these energy resources geospatially in order to determine optimal siting of renewable energy technologies; alternatively, if a renewable energy technology is sited at a specific site in order to meet a nearby load requirement (such as a solar home system), it is necessary to know what the resource availability is at that location, since microclimatic variability may make even nearby data sources irrelevant.

Examples of the products derived from the methodologies described below can be found for many areas around the world. One significant project that has recently been completed is the Solar and Wind Energy Resource Assessment (SWERA) Project, which provided high-resolution wind and solar resource maps for 13 countries around the world. SWERA was a project funded by the Global Environment Facility and was cost-shared by several technical organizations around the world: NREL; the State University of New York at Albany, the NASA's Langley Research Center, and the USGS/EROS Data Center in the U.S.; Riso National Laboratory in Denmark; the German Aerospace Institute (DLR); the Energy Resources Institute (New Delhi, India); and the Brazilian Spatial Institute (INPE) in Sao Jose dos Campos, Brazil. The United Nations Environment Programme (UNEP) managed the project. Besides the solar and wind resource maps and underlying data sets, a variety of other relevant data products came out of this program. All of the final products and data can be found on the SWERA archive, hosted at the UNEP/GRID site, collocated with the USGS/EROS data center in Sioux Falls, South Dakota (http://swera.unep.net).

For wind resource assessments, NREL's approach, known as Wind Resource Assessment Mapping System (WRAMS) relies on mesoscale numerical models such as MM5 or Weather Research and Forecasting (WRF), which can provide simulations of near-surface wind flow characteristics in complex terrain or where sharp temperature gradients might exist (such as land-sea contrasts). Typically, these numerical models use available weather data, such as the National Climatic Data Center's Integrated Surface Hourly (ISH) data network and National Center for Atmospheric Research-National Centers for Environmental Protection (NCAR-NCEP) reanalysis data as inputs. In coastal areas or island situations NREL's wind resource mapping also relies heavily on SeaWinds data from the Quickscat satellite to obtain near-shore and near-island wind resources. WRAMS also relies on Global Land Cover Characterization (GLCC) 1-km and Regional Gap Analysis Program (ReGAP) 200-m land cover data, as well as Moderate Resolution Imaging Spectroradiometer (MODIS) data from the Aqua and Terra Earth Observation System satellites, to obtain information such as percent of tree cover and other land use information. This information is used not only to determine roughness lengths in the numerical mesoscale models but also to screen sites suitable for both wind and solar development in the second component of the HOMER DSS.

The numerical models are typically run at a 2.5-km resolution. However, wind resource information is often reported at the highest resolution at which a digital elevation model (DEM) can provide. Globally this has traditionally been 1-km resolution; however, in some cases in the US 400-m DEM data are available. Furthermore, the Shuttle Radar Topology Mission has now been able to provide users with a 90-m DEM for much of the world. Thus, additional steps are needed beyond the 2.5-km resolution model output to depict wind resources at the higher resolutions offered by these DEM's. This can be accomplished by using a secondary high-resolution mesoscale model, empirical methods, or both. For example, with NREL's WRAMS methodology, GISD-based empirical modeling tools have been developed to modify results from the numerical models that appear to have provided unreliable results in complex-terrain areas.

The numerical models generally provide outputs at multiple levels above the ground. The WRAMS methodology provides values at a single specified height above the ground, nominally 50 m, or near the hub-height of modern-day large wind turbines (although with the recent advent of larger and larger wind turbines, hub heights are approaching 100 m, so this standard height designation is changing). Where measured data are used to assess wind resources, a simple "power law" relationship is used to extrapolate the measured data to the desired height (Elliott *et al.,* 1987), i.e.

$$V_R/V_a = (Z_R/Z_a),^{\alpha} \qquad (1)$$

where α, the power law coefficient, is normally assumed to be 1/7, V_R is the wind speed at reference height Z_R (nominally, 50 m), and V_a is the wind speed at the measurement height Z_a.

The output of the WRAMS methodology is typically a value of wind power density at every grid-cell representative of an annual average (in order to produce monthly values, the procedure outlined above would have to be repeated for each month of the year). For mapping purposes, a classification scheme has been set up that relates a "wind power class" to a range of wind power densities. The classification scheme ranges from 1 to >7, and applies to a specific height above ground. Normally, for grid-connected applications, a wind power class of 4 or above is best, while for small wind turbine applications where machines can operate in lower wind speeds, wind power class of 3 or above is suitable. Of course, the wind maps are not intended to identify sites at which large wind turbines can be installed, but rather are intended to provide information to developers on where they might most effectively install wind measurement systems for further site assessment. The maps also provide a useful tool for policy makers to obtain reliable estimates on the total wind energy potential for a region.

Other well-known approaches besides NREL's WRAMS methodology are also used to produce large-area wind resource mapping. For example, Riso National Laboratory calculates wind speeds within 200 m above the Earth's surface using the Karlsruhe Atmospheric Mesoscale Model (KAMM),. Although KAMM also uses NCEP/NCAR reanalysis data, the model is based on large-scale geostrophic winds, and simulations are performed for classes of different geostrophic wind. The classes are weighted with their frequency to obtain statistics for the simulated winds. The results can then be treated as similar to real observations to make wind atlas files for the Wind Atlas Analysis and Application Program (WAsP), which are employed to predict local winds at a much higher resolution than KAMM can provide. WAsP calculations are based on wind data measured or simulated at specific locations and includes a complex terrain flow model, a roughness change model, and a model for sheltering obstacles. More on WAsP can be found at http://www.wasp.dk/.

Due to the scarcity of high-quality, ground-based solar resource measurements, large-area solar resource assessments in the US have historically relied on the analysis of surface National Weather Service cloud cover observations. These observations are far more ubiquitous than solar measurements, and allowed NREL to develop a 1961 to 1990 National Solar Radiation Database for 239 surface sites. However, more recently in the US more and more reliance has been placed on GOES visible channel data to obtain surface reflectance information that can be used to derive high-resolution (~10-km) site-time specific solar resource data (see for example Perez, *et al.,* 2002). In fact, this approach has become commonplace in Europe, using Meteosat data. And the NASA Langley Research Center has recently completed a 20-year worldwide 100-km resolution Surface Solar Energy Data set derived from International Satellite Cloud Climatology Project data, which is derived from data collected by all of the Earth's geostationary and polar orbiting satellites (http://eosweb.larc.nasa.gov/sse).

The use of satellite imagery for estimating surface solar resource characteristics over large areas has been studied for some years, and Renné *et al.* (1999) published a summary of approaches developed around the world. These satellite-derived assessments require good knowledge of the aerosol optical depth over time and space, which can be obtained in part from MODIS and Advanced Very High Resolution Radiometer

(AVHRR) data from polar orbiting environmental satellites. The assessments provide information both on Global Horizontal Irradiance (GHI), which is useful for estimating resources available to flat plate collectors such as photovoltaic panels or solar water heating systems, and Direct Normal Irradiance (DNI), which is needed for determining the resources available to solar concentrators that track the sun.

Besides NREL and NASA, other organizations perform similar types of high-resolution solar resource data sets. For example, the German Space Agency (DLR) has been applying similar methods to Meteosat data for developing solar resource maps and data for Europe and northern Africa. DLR was also involved in the SWERA project and applied their methodologies to several SWERA countries.

Geospatial Toolkit

Recently, NREL has begun to format the solar and wind resource information into GIS software-compatible formats, and has incorporated this information, along with other geospatial data relevant to renewable energy development, into a Geospatial Toolkit (GsT). The GsT is a stand-alone, downloadable, and executable software package that allows the user to overlay the wind and solar data with other geospatial data sets available for the region, such as transmission lines, transportation corridors, population (load) centers, locations of power plant facilities and substations, land use and land form data, terrain data, etc. Not only can the user overlay various data sets of their choosing, there are also simple queries built into the toolkit, such as the amount of “windy” land (e.g. Class 3 and above) available within a distance of 10-km of all transmission lines (minus specified exclusion areas, such as protected lands). The GsT developed at NREL makes use of the Environmental Science and Research Institute’s (ESRI) MapObjects software, although other platforms, including on-line, Web-based platforms, could also be used.

In a sense, the GsT is a DSS, since it allows the user to manipulate resource information with other critical data relevant to the deployment of renewable energy technologies to assist decision makers in identifying and conducting preliminary assessments of possible sites for installing these systems and supporting renewable energy policy decisions. However, up to now NREL has only prepared GsT's for a few locations: the countries of Sri Lanka, Afghanistan, and Pakistan; Hebei Province in China; the state of Oaxaca in Mexico; and the state of Nevada in the US. By the time of publication of this chapter, additional toolkits may also be available. As with the resource data, all toolkits developed by NREL are available for download from NREL's Web site. Those toolkits developed under the SWERA project are also available from the SWERA Web site.

HOMER: NREL's Micropower Optimization Model

The primary decision support tool that makes up the DSS being described here is HOMER, NREL's Micropower Optimization Model. HOMER is a computer model that simplifies the task of evaluating design options for both off-grid and grid-connected power systems for remote, stand-alone, and distributed generation applications. HOMER's optimization and sensitivity analysis algorithms allow the user to evaluate the economic and technical feasibility of a large number of technology options and to account for variation in technology costs and energy resource availability. HOMER can also address system component sizing and the adequacy of the available renewable energy resource. HOMER models both conventional and renewable energy technologies:

Power sources:

- solar photovoltaic
- wind turbine
- run-of-river hydropower
- Generator: diesel, gasoline, biogas, alternative and custom fuels, co-fired
- electric utility grid
- microturbine
- fuel cell

Storage:

- battery bank
- hydrogen

Loads:

- daily profiles with seasonal variation
- deferrable (e.g., water pumping and refrigeration)
- thermal (e.g., space heating and crop drying)
- efficiency measures

In order to find the least cost combination of components that meet electrical and thermal loads, HOMER simulates thousands of system configurations, optimizes for lifecycle costs, and generates results of sensitivity analyses on most inputs. HOMER simulates the operation of each technology being examined by making energy balance calculations for each of the 8,760 hours in a year. For each hour, HOMER compares the electric and thermal load in the hour to the energy that the system can supply in that hour. For systems that include batteries or fuel-powered generators, HOMER also decides for each hour how to operate the generators and whether to charge or discharge the batteries. If the system meets the loads for the entire year, HOMER estimates the lifecycle cost of the system, accounting for the capital, replacement, operation and maintenance, and fuel and interest costs. The user can obtain screen views of hourly energy flows for each component as well as annual costs and performance summaries.

This and other information about HOMER are available on NREL's Web site: http://www.nrel.gov/homer/. The Web site also provides extensive examples of how HOMER is used around the world to evaluate optimized hybrid renewable power systems to meet load requirements in remote villages. Figure 1 shows a typical example of an output graphic available from HOMER.

In order to accomplish these tasks, HOMER requires information on the hourly renewable energy resources available to the technologies being studied. However, typically hour-by-hour wind and solar data are not available for most sites. Thus, the user is requested to provide monthly or average information on solar and wind resources; HOMER then uses an internal weather generator to provide the best estimate of a simulated hour-by-hour data set, taking into consideration diurnal variability if the user can provide an indication of what this should be. However, these approximations represent a source of uncertainty in the model. For those locations where a GsT is available, the GsT offers a mechanism for the user to easily ingest data from the toolkit into HOMER for the specific location of interest. However, since the toolkit contains only monthly solar and wind data, the limitations described above still apply. More information on the weather generator can be found in the HOMER Help files.

The HOMER developers have implemented various methods to facilitate access to reliable resource data that provide some of the input for simulations. For example, a direct link with the NASA SSE data site enables the user to download monthly and annual solar data from any location on Earth. The 100-km resolution NASA data have become a benchmark of solar resource information, due to the high quality of the modeling capability used to generate the data, the fact that the SSE is validated against numerous ground stations, and the fact that it is global in scope and now covers a 20-year period. However, the data set is still limited by a somewhat coarse resolution and no validation in areas where ground data do not exist. The procedures used to generate the SSE also have problems where land-ocean interfaces occur, and in snow-covered areas.

Linking HOMER to higher-resolution regional solar data sets would likely improve these uncertainties somewhat, but in general these data sets are also limited to monthly and seasonal values. However, since these methods rely on geostationary satellite data that provide frequent imagery of the Earth's surface, an opportunity exists to produce hourly time series data for up to several years at a 10-km resolution. This option will require significant data storage and retrieval capabilities on a server, but such a possibility now exists for future assessments.

Wind data available to HOMER is also generally limited to annual and at best monthly values. The standard HOMER interface allows the user to also designate a Weibull "k" value if this information is available. The Weibull k is a statistical means of defining the frequency distribution of the long-term hourly wind speeds at a location; this value can vary substantially depending on local terrain and microclimatic conditions. HOMER also has a provision for the user to designate the diurnal range of wind speeds and the timing when maximum and minimum winds occur. This information then provides improved simulation of the hour-by-hour wind values. The difficulty is that there may be applications where even these statistical values are not known to the user and are not available from the standard wind resource maps produced for a region, but this limitation may not be critical and requires further study to determine the impact on model output uncertainties.

2b. Access to the HOMER DSS

HOMER was originally developed and has always been maintained by the National Renewable Energy Laboratory. The model can be downloaded free of charge from NREL's Web site at http://www.nrel.gov/homer/default.asp. The user is required to register, and registration must be updated every six months. The Web site also contains a variety of guides for getting started and using the software.

Resource information required as input to HOMER is generally freely available at the Web sites of the institutions developing the data. These institutions also generally maintain and continuously update the data. For example, renewable energy resource information can be found in several places on NREL's Web site, such as http://rredc.nrel.gov or www.nrel.gov/GIS. NASA solar energy data, which can be easily input to HOMER, is available at http://eosweb.larc.nasa.gov/sse. In fact, there is a specific feature built into HOMER that automatically accesses and inputs the SSE data for the specific location that the model is analyzing. Wind and solar resource data for the 13 SWERA countries can be found at http://unep.swera.net. This Web site is currently undergoing expansion and upgrading by the USGS/EROS Data Center in Sioux Falls, SD, and will eventually become a major clearing house for resource data from around the world in formats that can be readily ingested into tools such as HOMER.

2c. Definition of HOMER information requirements

The ideal input data format to HOMER is an hourly time series of wind and solar resource data covering a complete year (8,760 values). In addition, the wind data should be representative of the wind turbine hub height that is being analyzed within HOMER. Unfortunately data sets such as these are seldom available at the specific locations for which HOMER is being applied. More typically, the HOMER user will have to identify input data sets from resource maps (even within the GsT, the resource data are based on what is incorporated into the map, which, in the case of wind, may represent only a single annual value). Because monthly and annual mean data are more typically available, HOMER has been designed to take monthly mean wind speeds (in m/s) and monthly mean solar resource values (in kw-h/m^2-day). In the case of wind, HOMER also allows for the specification of other statistical parameters related to wind speed distributions and diurnal characteristics. Furthermore, if the wind data available for input to HOMER do not represent the same height above the ground as the wind turbine's hub height being analyzed, HOMER has internal algorithms to adjust for this. The user must specify the height above the ground for which the data represent, and a power law conversion adjusts the wind speed value to the hub height of the specific wind turbine being analyzed. HOMER then utilizes an internal weather generator that takes the input information and creates an hour-by-hour data profile representing a one-year data file. Then, HOMER calculates turbine energy output by converting each hourly value to the energy production of the machine using the manufacturer's turbine power curve.

Besides the mean monthly wind speeds, the statistical parameters required by HOMER to generate the hourly data sets include the following:

- The altitude above sea level (to adjust for air density, since turbine performance is typically rated at sea level);
- The Weibull k value, which typically ranges from 1.5 to 2.5, depending on terrain type;
- An auto-correlation factor, which is a measure of how strongly the wind speed in 1 hour depends (on average) on the wind speed in the previous hour (these values typically range from 0.85 to 0.90);
- A diurnal pattern strength, which is a measure of how strongly the wind speed depends on the time of day (values are typically 0.0 to 0.4); and
- The hour of the peak wind speed (over land areas this is typically 1400 to 1600 local time)

In the US as elsewhere, wind resource maps often depict the resource in terms of wind power density, in units of watts-m^{-2} rather than in wind speeds. In this case, the wind power density must be converted back to a mean wind speed. The relationship between wind power density (P) and wind speed (v) is given as follows:

$$P = \tfrac{1}{2}\rho\sum_{i} v_i^3, \qquad (2)$$

where ρ is the density of the air and *i* is the individual hourly wind observation. Since the frequency distribution of wind speed over the period of a year or so follows a Weibull distribution shape, the wind power density can be converted back to a wind speed if the "k" factor in the Weibull distribution is known, as well as the height above sea level of the site (to determine the air density).

2d. Access to and use of the HOMER DSS among the federal, state, and local levels

Because of the easy access to HOMER and to the related resource assessment data products, the HOMER DSS is freely available to all government and private entities in the US and worldwide. Thousands of users from all economic sectors are using HOMER to evaluate renewable energy technology applications, particularly for off-grid use.

2e. Variation of the HOMER DSS by geographic region or characteristic

A key feature of HOMER is the evaluation of specific renewable energy technologies and related energy systems for different regions and for different applications. The HOMER model contains information on renewable energy technology characteristics; however, these characteristics, such as power curves of difference wind turbine models, generator fuel curves, and other factors are not affected by location. Because of the location-specific dependency of resource data, use of data that is not representative of the specific region of analysis will introduce additional uncertainties in the model results. Thus, the user should evaluate the accuracy and relevancy of any default information that is built into HOMER, or any resource data chosen as input to HOMER before completing the final analyses.

3. Observations used by the HOMER DSS now and of potential use in the future

This section focuses on the Earth observations (of all types, from remote sensing and *in situ*) used or of potential use in the HOMER DSS.

3a. Kinds of observations being used

In the previous section we provided a description of the renewable energy resource assessment related to solar and wind technologies that are required as input to HOMER when these technologies are being modeled. As noted in that section, developing this resource information requires the use of a variety of Earth observations. In this section we list out these observations for each resource category, as well as other types of observations relevant to the HOMER DSS.

Wind Resources

The ideal observational platform for obtaining reliable wind resource data to be input into HOMER would be calibrated wind speed measurements from a meteorological tower installed at the location of interest. These measurements should be obtained at the hub height of the wind turbine being modeled, should be of sufficient sampling frequency to provide hourly measurements, and should be of sufficient quality and duration to result in at least one full year of continuous measurements. Although measurements of this quality are typically necessary at project sites where significant investments in large grid-connected wind turbines are anticipate, and where a decision has already been made to implement a large-scale project, it is extremely rare that this level of observation is available for most HOMER applications, where the user is examining potential applications for proposed projects. Thus, some indirect means to establish wind characteristics at a proposed site, such as extrapolating wind resource measurements available from a nearby location or developing a wind resource map such as described in Section 2, is required. The major global data sets typically used by NREL for wind resource assessment are summarized in table 1.

More discussion on some of these data sets is provided below.

Surface Station Data

In the US, as well as in most other countries, the main source of routine surface wind observations would be observations from nearby national weather stations, such as those routinely maintained to support aircraft operations at airports. These data can be made available to the user from the National Climatic Data Center (NCDC) in the form of the Integrated Surface Hourly (ISH) data set. This database is composed of worldwide surface weather observations from about 20,000 stations, collected and stored from sources such as the Automated Weather Network (AWN), the Global Telecommunications System (GTS), the Automated Surface Observing System (ASOS), and data keyed from paper forms (see, http://gcmd.nasa.gov/records/GCMD_C00532.html).

Satellite-Derived Ocean Wind Data

Ocean wind data can be obtained from the SeaWinds Scatterometer (see http://manati.orbit.nesdis.noaa.gov/quikscat/) mounted aboard NASA's Quick Scatterometer (QuickSCAT) satellite. QuickSCAT was launched on June 19, 1999 in a sun-synchronous polar orbit. A longer-term ocean winds data set is available from the Special Sensor Microwave/Imager (SSM/I) data products as part of NASA's Pathfinder Program. The SSM/I geophysical dataset consists of data derived from observations collected by SSM/I sensors carried onboard the series of Defense Meteorological Satellite Program (DMSP) polar orbiting satellites (see http://www.ssmi.com/ssmi/ssmi_description.html#ssmi). An example of how Scatterometer data were used in support of a wind resource assessment in Pakistan is provided in figure 2 (see also http://www.nrel.gov/international/rr_assess_pakistan.html). Airborne or space borne Synthetic Aperture Radar systems can also provide information on ocean wind data, although these data are not commonly used for this purpose in the US, since Scatterometer data products are more readily and freely available.

Reanalysis Upper Air Data

The US reanalysis data set was first made available in 1996 to provide gridded global upper air and vertical profiles of wind data derived from 1,800 radiosonde and pilot balloon observations stations (Kalnay, *et al.* 1997). The reanalysis data were prepared by NCAR-NCEP and can be found at http://www.cdc.noaa.gov/cdc/reanalysis/. An early analysis of the data set (Schwartz, George, and Elliott, 1999) showed that for wind resource assessments the dataset was a promising tool for gaining a more complete understanding of vertical wind profiles around the world but that discrepancies with actual radiosonde observations still existed. Since that time, continuous improvements have been made to the NCAR-NCEP dataset, and it is has become an ever-increasingly important data source for contributing to reliable wind resource mapping activities.

Digital Terrain Data

Digital Elevation Models (DEM) have been accessed from the USGS/EROS data center. These models consist of a raster grid of regularly spaced elevation values that have been derived primarily from the USGS topographic map series. The USGS no longer offers DEMs, and for the US these can now be accessed from the National Elevation Dataset (http://ned.usgs.gov/). The Shuttle Radar Topographic Mission (SRTM) offers much higher resolution terrain data sets, which are now beginning to be used in some wind mapping exercises. These are also being distributed by USGS/EROS under agreement with NASA (http://srtm.usgs.gov/).

Digital Land Cover Data

Land cover data are used to estimate roughness length parameters required for the mesoscale meteorological models used in the wind mapping process. Data from the Global Land Cover Characterization dataset provide this information at a 1-km resolution (see http://edcsns17.cr.usgs.gov/glcc/background.html). The Moderate Imaging Spectroradiometer (MODIS) is used to obtain global percent tree cover values at a spatial resolution of 0.5 km (Hansen, *et al.,* 2003). Existing natural vegetation is also being mapped at a 200-m resolution as part of the USGS Regional Gap Analysis program. Gap analysis is a scientific method for identifying the degree to which native animal species and natural communities are represented in our present-day mix of conservation lands (Jennings and Scott, 1997).

Solar Resources

As with wind, the ideal solar resource data set for incorporation into HOMER would be data derived from a quality, calibrated surface solar measurement system consisting of a pyranometer and a pyrheliometer that can provide a continuous stream of hourly data for at least one year. Such data are seldom available at the site for which HOMER is being applied. Although interpolation to nearby surface radiometer data sets can be accomplished with reasonable reliability, we usually resort to an estimation scheme to derive an *in-situ* data set. The solar resource assessments that NREL and others undertake make use of several different observational datasets, such as ground-based cloud cover measurements, satellite-derived cloud cover measurements, or the use of the visible channel from satellite imagery data. The major global data sets used for solar resource assessments are summarized in table 2.

More discussion on some of these data products is described below.

World Radiation Data Center

Since the early 1960s the World Radiation Data Center, located at the Main Geophysical Institute in St. Petersburg, Russia, has served as a clearinghouse for worldwide solar radiation measurements collected at national weather stations. The WRDC is under the auspices of the World Meteorological Organization. A Web-based data set was developed by NREL in collaboration with the WRDC and can be accessed at http://wrdc-mgo.nrel.gov/. This data archive covers the period 1964 to1993. For more recent data, the user should go directly to the WRDC home page at http://wrdc.mgo.rssi.ru/.

Aerosol Optical Depths (AOD)

After clouds, atmospheric aerosols have the greatest impact on the distribution and characteristics of solar resources at the Earth's surface. However, routine *in-situ* observations of this parameter have only recently begun. Consequently, a variety of surface-based and satellite-based observations are used to derive the best information possible of the temporal and spatial characteristics of the atmospheric AOD. The most prominent of the surface data sets is the AERONET (http://aeronet.gsfc.nasa.gov/), a network of automated multiwavelength sun photometers located around the world. This network also has links to other networks, where the data may be less reliable. AERONET data can be used to provide ground-truth data for different satellite sensors that have been launched on a variety of sun-synchronous orbiting platforms since the 1980s, such as the Total Ozone Mapping Spectrometer (TOMS), the Advanced Very High Resolution Radiometer (AVHRR), the Moderate Resolution Imaging Spectroradiometer (MODIS), and the Multi-Angle Imaging Spectroradiometer (MISR), the latter two mounted on NASA's Terra satellite. As noted by Gueymard (2003) determination of AOD from satellite observations is still subject to inaccuracies, particularly over land areas, due to a variety of problems such as insufficient cloud screening or interference with highly reflective surfaces. The Global Aerosol Climatology Project (GACP), established in 1998 as part of the NASA Radiation Sciences Program and the Global Energy and Water Experiment (GEWEX), has as its main objectives to analyze satellite radiance measurements and field observations in order to infer the global distribution of aerosols, their properties, and their seasonal and interannual variations and to perform advanced global and regional modeling studies of the aerosol formation, processing, and transport (http://gacp.giss.nasa.gov/).

Other sources of aerosol optical depth data include the Global Ozone Chemistry Aerosol Transport (GOCART) model (http://code916.gsfc.nasa.gov/People/Chin/gocartinfo.html) which is derived from a chemical transport model. An older dataset, the Global Aerosol Dataset (GADS), which can be found at http://www.lrz-muenchen.de/~uh234an/www/radaer/gads.html, is a theoretical data set providing aerosol properties averaged in space and time on a 5^0 x 5^0 grid. (Koepke, *et al.,* 1997).

Other Renewable Energy Resources

Although the scope of this chapter focuses on wind and solar energy resources, it is evident that many of the Earth observation data sets listed above can apply to other renewable energy resources as well. For example, hydropower resources can be determined by analysis of high resolution DEM data, along with knowledge of the rainfall amounts over specific watersheds and the land use characteristics of these watersheds. Biomass resource assessments can be enhanced through use of MODIS data as well as other weather-related data, and through evaluation of MODIS and AVHRR data to determine the Normalized Vegetation Index (NVI).

3b. Limitations on the usefulness of observations

In the absence of direct solar and wind resource measurements at the location for which HOMER is being applied, the observations described in Section 3a, when used in the wind and solar resource mapping techniques described in Section 2, will together provide useful approximations of the data required as input to HOMER. However, the observations all have limitations in that they do not explicitly provide direct observation of the data value required for the mapping techniques but only approximations based on the use of algorithms to convert a signal into the parameter of interest. These limitations for some of these data sets can be summarized here:

Surface Station Data: These are generally not available at the specific locations at which HOMER would be applied, so interpolation is required. Furthermore, they generally do not have actual solar measurements, but rather proxies for these measurements (i.e., cloud cover). The wind data are generally collected at 10 m above the ground or less, and the anemometer may not be in a well-exposed condition. When the station observations are derived from human observations, they represent samples of a few minutes duration every 1 or 3 hours; therefore, many of the observations are missing. For those stations that have switched from human observations to Automated Surface Observation Stations (ASOS), the means of observation have changed significantly from the human observations, representing a discontinuity in long-term records. Occasionally, the location of the station is changed without changing the station ID number, which can also cause a discontinuity in observations. Similarly, equipment changes can cause a discontinuity in observations

Satellite-Derived Ocean Wind Data: These data are not based on direct observation of the wind speed at 10 m above the ocean surface, but rather from an algorithm that infers wind speeds based on the wave height observations provided by the scatterometers or Synthetic Aperture Radar

Satellite-Derived Cloud Cover and Solar Radiation Data: These data sets are derived from observations of the reflectance of the solar radiation from the Earth-atmosphere system. Although it could be argued that this method does provide a direct observation of clouds, the solar radiation values are determined from an algorithm that converts knowledge of the reflectance observation, the incoming solar radiation at the top of the atmosphere, and the transmissivity characteristics of the atmosphere to develop estimates of solar radiation.

Aerosol Optical Depth: Considerable research is underway to improve the algorithms used to convert multi-spectral imagery of the Earth's surface to aerosol optical depth. The satellite-derived methods have additional shortcomings over land surfaces, where irregular land-surface features make application of the algorithms complicated and uncertain.

3c. Reliability of the observations

For those observations that provide inputs to the solar and wind resource data, their reliability can vary from parameter to parameter. Generally all of the observations used to produce data values required for solar and wind assessments have undergone rigorous testing, evaluation, and validation. This research has been undertaken by a variety of institutions, including the institutions gathering the observations (e.g., NASA and NOAA) as well as the institutions incorporating the observations into resource mapping techniques (e.g., NREL). Many of the satellite-derived observations of critical parameters will be less reliable than *in-situ* observations; however, satellite-derived observations must still be used due to the scarcity of *in-situ* measurement stations.

3d. What kinds of observations could be useful in the near future

All of the observations currently available will continue to be of critical value in the near future. For renewable energy resource mapping, improved observations of key weather parameters (wind speed and direction at various heights above the ground and over the open oceans at higher and higher spatial resolutions, improved ways of differentiating snow cover and bright reflecting surfaces from clouds, etc.) will always be of value to the renewable energy community. New, more accurate methods of related parameters such as aerosol optical depth would result in improvements in the resource data. All of these steps will lead to improvements in the quality of outputs from renewable energy decision support tools such as HOMER.

4. Uncertainty

Application of the HOMER DSS involves a variety of input data types, all of which can have a level of uncertainty attached to them. HOMER addresses uncertainties by allowing the user to perform sensitivity analyses for any particular input variable or combination of variables. HOMER repeats its optimization process for each value of that variable and provides displays to allow the user to see how results are affected. An input variable for which the user has specified multiple values is called a sensitivity variable, and users can define as many of these variables as they wish. In HOMER, a “one-dimensional” sensitivity analysis is done if there is a single sensitivity variable, such as the mean monthly wind speed. If there are two or more sensitivity variables, the sensitivity analysis is “two” or “multi-dimensional.” HOMER has powerful graphical capabilities to allow the user to examine the results of sensitivity analyses of two or more dimensions. This is important for the decision maker, who must factor in the uncertainties of input variables in order to make a final judgment on the outputs of the model.

The amount of uncertainty associated with resource data is largely dependent on how the data are obtained and on the nature of the analysis being undertaken. For some types of analyses, very rough estimates of the wind resource would be sufficient; for others, detailed hourly average data based on surface measurements would be necessary. Quality *in-situ* measurements of wind and solar data in formats suitable for renewable energy applications over a sufficient period of time (one year or more) can have uncertainties of less than ±3% of the true value. However, when estimation methods are required, such as the use of Earth observations and modeling and empirical techniques, uncertainties can be as much as ±10% or more. These uncertainties are highest for shorter-term data sets, and are lower when annual average values are being used, since throughout the year errors in the estimation methods have a tendency to compensate among the individual values.

Based on wind turbine and solar technology operating characteristics, it is possible that the error in estimating a renewable energy system performance over a year is roughly linear to the error in the input resource data. For example, for wind energy systems, even though the power of the wind available to a wind turbine is a function of the cube of the wind speed, it turns out that the turbine operating characteristics, where turbines typically do not provide any power at all until a certain threshold speed is reached, and then the power output increases linearly with wind speed until the winds are so high that the turbine must shut down. This results in an annual turbine power output that is roughly linear to the mean annual wind speed for certain mean wind speed rangers. This would mean that, in some cases, an uncertainty in the annual wind or solar resource of ±10% results in an uncertainty of expected renewable energy technology output of approximately ±10%.

5. Global change information and the HOMER DSS

This section expands the discussion of the HOMER DSS to include the relationship of HOMER and its input data requirements with global change information

5a. Reliance of HOMER DSS global change information

As shown in the previous section, a number of observations that provide information on global change are also used in either direct or indirect ways as input to HOMER. These observations related primarily to the renewable energy resource information that is required for HOMER applications. Renewable energy system performance is highly dependent on the local energy resources available to the technologies. The extent and characteristics of these resources is driven by weather and local climate conditions, which happens to be the primary area in which Earth observational systems monitoring climate change are addressing. Thus, as users seek access to observations to support renewable energy resource assessments, they will invariably be seeking certain global change observational data.

Specifically, users will be seeking global change data related to atmospheric properties that support the assessment of solar and wind energy resources, such as wind and solar data, and atmospheric parameters important for estimating these data. For example, major data sets used in solar and wind energy assessments include long-term reanalysis data, climatological surface weather observations, and a variety of satellite observations from both active and passive onboard remote sensors.

Key factors in affecting the choice of these observational data are their relevance to conducting reliable solar and wind energy resource assessment, their ease of access, and low or no cost to the user. The extensive list of observational data being used in the assessment of renewable energy resources represents strong leveraging of major, taxpayer-supported observational programs that are geared primarily for global change assessment.

There is also an important consideration regarding the potential influence of long-term climate change on the renewable energy resources that are used as input into HOMER. Through the Intergovernmental Panel on Climate Change there has been a significant improvement in the reliability and spatial resolution of General Circulation Models (GCM) used to estimate the impacts of greenhouse gas emissions on climate change. As weather patterns change under changing climate conditions, wind and solar energy resources at a specific location can also change over time. The GCM results indicate that these renewable energy resources can be measurably different 50 to 100 years from now than today in specific locations and regions. These changes may have a noticeable impact on the results of HOMER simulations in the future; however, significant uncertainties exist in GCM results. Until these uncertainties are reduced sufficiently, implementation of GCM results will produce unreliable HOMER simulations.

5b. How the HOMER DSS can support climate-related management decision-making among US government agencies

Although HOMER was not intentionally designed to be a climate-related management decision-making tool, the HOMER DSS has attributes that can support these decisions. For example, as we explore mechanisms for mitigating the growth of carbon emissions in the atmosphere, the HOMER DSS can be deployed to evaluate how renewable energy systems can be used cost-effectively to displace energy systems dependent on fossil fuels. Clearly, the science results and global change data and information products coming out of our reanalysis and satellite-borne programs are of critical importance to HOMER for supporting this decision-making process. Given that the pertinent observational data sets have been developed primarily by federal agencies, these data sets tend to be freely available or available at a relatively small cost, given the costs involved in making the observations in the first place. However, as we have noted in previous sections, the use of global change observations as input to the resource assessment data required by HOMER is not the optimal choice of data; ideally, *in-situ* (site-specific) measurements of wind and solar data relevant to the technologies being analyzed would be the most useful and accurate data to have for HOMER, if they were available.