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Facilitating Digital Analysis and Exploration in Solar Energy Science and Technology through Free Computer Applications †

Osama A. Marzouk

Department of Technical Engineering, College of Engineering, University of Buraimi, Al Buraimi 512, Oman; osama.m@uob.edu.om

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Abstract: A number of free computer applications exist for designing solar power systems and predicting their performance. Among the various tools, three reputable ones were used while assessing different solar energy technologies; these were either the concentrated solar power (CSP) type or the photovoltaic (PV) type. Various types of digital data, including computer modeling files, tabulated values, and illustrative views for simulations conducted by the desktop software program Energy3D (by the Concord Consortium) for analyzing solar systems are described and made publicly accessible by the author. Thus, the interested reader can reproduce or customize simulations. The modeled solar power systems include solar farms with a fixed or moving array of panels, linear Fresnel reflectors, parabolic troughs, parabolic dishes, and solar towers. Supporting benchmarking data are also included, which are prediction reports for three PV systems using the cloud-based application PVGIS (Photovoltaic Geographical Information System), developed by the European Commission Joint Research Center (JRC). These PV systems are related to three systems modeled via Energy3D, and thus help in validation. Another set of benchmarking data comes from another cloud-based application for PV systems, which is PVWatts, provided by the National Renewable Energy Laboratory (NREL) of the United States Department of Energy (DoE). This paper describes data used in the analysis as guiding examples, giving an opportunity for gaining knowledge and skills in the research areas of solar energy science and technology. It also briefly discusses a fourth free solar energy tool, 'Aladdin' (by the Institute for Future Intelligence), which possesses artificial intelligence capabilities. The data consist of a total of 59 digital files, divided into in 7 computer folders. Each folder contains a number of binary and/or text files, ranging from 2 to 18.

Keywords: solar energy technology; computer model; Energy3D; PVGIS; PVWatts; Aladdin

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1. Introduction

Renewable energy sources include hydropower, solar (either photovoltaic or concentrated solar power), wind (either offshore or onshore), bioenergy (either biomass or biogas), geothermal, ocean (either tidal or wave), and green hydrogen (hydrogen generated using renewable energy sources). According to the second edition (2022) of the World Energy Transitions Outlook (WETO) of the International Renewable Energy Agency (IRENA) [1], the share of renewable energy of the total worldwide electricity generation (more than 26,900 TWh) in 2019 was 26.4%. The share of fossil fuels was 63.2%, and the share of nuclear energy was 10.4%. Out of the 7400 GW capacity of global electricity generation in 2019, the share of renewable energy exceeded 2500 GW (33.8%), with solar energy contributing 580 GW (about 7.8% of the global generation capacity). In order to limit global warming to 1.5 °C, a minimum pace of transition to renewable energy is needed such that the greenhouse gas emissions to the atmosphere are properly reduced. In the 1.5 °C scenario, the share of renewable energy in the global electricity capacity should rise to 76% in 2030 (with the share of solar energy alone being about 40%), and then further to 92% in 2050 (with the share of solar energy alone being about 50%). The current photovoltaic (PV) systems and those in the 2050 energy outlook remain the dominant type of solar systems, while the concentrated solar power (CSP) systems remain the minor type.

The ability to conveniently explore the performance of solar power systems without a need for an academic study or extensive training in the field of solar energy helps in the spread of this type of renewable energy to a wide range of users. Numerical simulations through an intuitive graphical user interface (GUI) and no-cost computer application are excellent methods for: (1) increasing the awareness of the benefits of solar systems; (2) taking informed decisions regarding investment in them; and (3) optimizing solar systems designs under given constraints. Major difficulties that might be faced when using a computer application for predicting the electricity generated from a prospective solar power system include: (1) required specialized knowledge in the field of solar energy; (2) cost incurred in purchasing or subscribing in the computer application used in the solar system modeling if it is proprietary and not released freely to the public; (3) limited access to reliable meteorological data with a high geographical resolution such that the user can conveniently benefit from such data in a solar system modeling at a generic desired geographic location not limited to specific cities or certain zones; (4) lack of optimization capabilities in the modeling application, where the application performs numerical simulation only for the set of conditions specified by the user rather than searching and recommending one of multiple options; (5) lack of financial feasibility analysis for the solar power system during the anticipated life of that system; and (6) lack of summary reports for decision makers using a simple content not including specialized technical terms, with options for non-English languages and with explanatory techno-economic performance diagrams.

This work may be viewed as serving two purposes. First, it gives an overview of four applications for modeling solar power systems. All these applications are available for use to the public without cost, subscription, or even registration. Second, it acts as a companion document for another published research article [2] that utilized three modeling applications out of the four mentioned here. In particular, it describes simulation files and raw results produced during the use of these applications as exemplary cases completed successfully. Thus, the interested user can use them as validation data or for gaining hands-on experience with regard to these useful applications. All the data discussed are available in the Data Availability Statement of this article.

2. Methods and Data Generation

The current work is based on numerical modeling of envisioned (not already existing) solar power systems using different computer programs. These simulations yield results about the expected electric energy (as alternating current (AC) electricity) to be generated during a specified period of time for each system. The raw results can be in the form of a single cumulative value, detailed tables, charts, or summary page. They can be processed further and recast in a desired format. The simulation programs used are:

- The offline application Energy3D, version 8.7.4 (2022) [3].
- The web application PVGIS, version 5.1 [4,5].
- The web application PVWatts (also called PVWatts Calculator) [6,7].

Regarding the data discussed here; they are dominantly related to Energy3D. They were generated by running offline computer simulations using a Microsoft Windows operating system. Then, tabulated numerical predictions of electricity generation were copied from the program and pasted in a new blank text file. An image from the program that demonstrates the three-dimensional layout of each modeled solar power system was exported as a png (portable network graphics) image file, using an exporting capability built into the program itself. This process took place twice, resulting in two different views for each system. The simulation file (with the ng3 file extension) that was used by Energy3D for each modeled solar power system was saved. This (ng3) file can be opened by the Energy3D program, to access the three-dimensional model for analysis or modification. The file extension (ng3) represents a native file format for the computer models made by Energy3D. These files have a binary format; they are not human-readable through a text editor.

The other part of the data was generated by running online computer simulations using PVGIS and PVWatts, within the Google Chrome internet browser. PVGIS has a built-in feature enabling the user to export a simulation summary as a single-page pdf file, which contains not only properties of the modeled solar system, but also the expected monthly electricity output from the system as a bar graph and as a table. The PVWatts application provides an online web page with the summary of the simulation. This page is then saved as a pdf file using features available in Google Chrome, so that the data are archived and can be accessed offline conveniently.

All the data correspond to one geographic location, namely the city of Muscat (the capital of the Sultanate of Oman). In Energy3D, the city (Muscat) was selected from a list of available locations in an internal database. The corresponding latitude for Muscat in the program is 23° (it was adopted since it was the only location within the Sultanate of Oman that is available in Energy3D). In the PVGIS website, the location was specified manually via a pair of latitude and longitude coordinates, as (23.583889° north, 58.407778° east). When displayed in the report, the coordinates were shown with 3 decimal places as (23.584°, 58.408°). In the PVWatts website, when the location requested was typed (in a text box within the initial interface window) as "muscat", this name was correctly recognized by the website, as evidenced by an interactive map displayed around the location of Muscat, with a mark placed appropriately at Muscat itself. The PV module type was set to (Premium), and the inverter efficiency was set to 95%. The peak ideal power for the PV system with fixed PV panels was set to 1212.75 kW; and the ground coverage ratio (GCR) was set to 0.598475. The peak power for the PV system with two-axis solar tracking panels was set to 81.900 kW, and the ground coverage ratio was set to 0.253885. These specific values help in making the models compatible with their counterparts in Energy3D.

For all the three solar simulation tools used, no data cleaning/correction was needed for the raw data, because no incidence of mistaken or missing data was encountered.

The web application Aladdin is described very briefly, without being utilized. It is the most recent application of the four covered here for modeling solar systems [8]. It supports biologically inspired methods for optimization. One of them is the genetic algorithms (GA), which is an adaptive selection method mimicking the biological theory of selection. Another available method is particle swarm optimization (PSO), which is based on the motion of a bird flock searching for food sources.

3. Results

This section describes the simulation data for the three utilized simulation applications, such that they can be understood or properly utilized.

3.1. Type of Simulation Data

- Binary (not human-readable) computer files:
    a. Energy3D computer model files (9 .ng3 files);
- Images exported from a software program (not taken by a camera):
    a. Energy3D model views (18 .png files);
- Tables (in the form of text files, having 2 columns and either 12 rows "if per-day results, with a value for each of the 12 calendar months" or 24 rows "if per hour"):
    a. Energy3D prediction tables, kWh per day (9 .txt files);
    b. Energy3D prediction tables, kWh per hour on 21-December (9 .txt files);
    c. Energy3D prediction tables, kWh per hour on 21-June (9 .txt files);
- pdf (portable document format) files:
    a. PVGIS prediction reports for three PV systems (3 .pdf files);
    b. PVWatts prediction summaries for two PV systems (2 .pdf files);

3.2. File Structure of Simulation Data

The data comprise 59 computer files organized in 7 folders. Each folder contains between 2 and 18 files. The files in each folder share the same file extension and purpose; they differ only in the solar power system they correspond to. The folder names are:

1. Energy3D models.
2. Energy3D model views.
3. Energy3D prediction tables, kWh per day.
4. Energy3D prediction tables, kWh per hour on 21 December.
5. Energy3D prediction tables, kWh per hour on 21 June.
6. PVGIS prediction reports for 3 PV systems.
7. PVWatts prediction reports for 2 PV systems.

4. Discussion

In this section, a single attractive feature is selected to be emphasized about each of the four free simulation applications for solar systems mentioned in this work.

4.1. Energy3D

The model files tend to be small in size (ranging from 27 kilobytes for the CSPt system to 158 kilobytes for the CSPh system). Thus, they are easy to share and distribute.

4.2. PVGIS

This application allows the user to define the horizon profile around the site being modeled (instead of using a default built-in profile based on the natural terrains). This means that shades caused by nearby structures or trees can be accounted for.

4.3. PVWatts

The embedded technical reference (providing explanatory text, graphics, formulas, and tables) can be conveniently displayed from many locations to provide simple explanation of parameters that the user selects or enters.

4.4. Aladdin

The solar updraft tower (SUT) can be modeled. This is a different type of renewable energy system that utilizes solar heat to produce hot-air movement.

5. Conclusions

Four free computer applications for modeling solar power systems were discussed. These are: Energy3D, PVGIS, PVWatts, and Aladdin. Three of them (all except Aladdin) were used with different examples of photovoltaic or concentrated solar power systems. Examples of simulation data were made available and described for potential use.

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Data Availability Statement: The data presented in this study are openly available in Mendeley Data at https://doi.org/10.17632/gg49jmrfcd.1. The data files are stored in a compressed archive file named (Data.zip), with a total size of 7 megabytes (MB).

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Nomenclature

Aladdin	a web application for analyzing photovoltaic solar systems, as well as concentrated solar power systems (by the Institute for Future Intelligence, IFI).
GCR	ground coverage ratio. It is a number representing the total projected (flat) area of the solar elements, such as PV modules or CSP dishes, divided by the land area of the foundation supporting these solar elements. It is a dimensionless measure of the geometric compactness of a solar power system, regardless of the generated electricity.
CSP	concentrated solar power.
CSPd	concentrated solar power system example with 16 parabolic dishes. Each dish has a rim diameter of 8 m. The dishes are curved mirrors that can continuously change their angular direction to be facing the solar disc.
CSPF1	concentrated solar power system example with twenty linear Fresnel reflectors and one heat absorber located amid the reflectors. Each reflector has a length of 36 m, and is aligned parallel to a south–north line (thus, the reflector has one of is longitudinal tips near the northern edge of the foundation, while the other tip is near the southern edge of it; the two tips are 36 m apart). The reflectors continuously change their tilt (inclination) angles to optimize their function as reflectors of the solar irradiation to the common absorber.
CSPF2	concentrated solar power system example with twenty linear Fresnel reflectors and two heat absorbers located at opposite sides outside the reflectors zone. Each reflector has a length of 36 m, and is aligned parallel to a south–north line. The reflectors continuously change their tilt angles to optimize their function as reflectors of the solar irradiation to either of the two absorbers.
CSPh	concentrated solar power system example with 650 heliostats and 2 solar towers located amid the heliostats, next to each other. Each heliostat has a flat rectangular reflection area of 15 m^2. The heliostat mirrors can continuously change their orientation angles to optimize their function as reflectors of the solar irradiation to the top of either of the two receiving towers.
CSPt	concentrated solar power system example with seven parabolic troughs. Each trough is a curved mirror reflector with a length of 64 m, aligned parallel to a south–north line. The troughs can continuously change their inclination angle to receive the solar beams as perpendicular as possible.
Energy3D	an offline application for analyzing photovoltaic solar systems, as well as concentrated solar power systems (by the Concord Consortium).
GW	gigawatt (10^9 watts).
IFI	Institute for Future Intelligence.
JCR	Joint Research Center of the European Commission (EC).
kW	kilowatt (10^3 watts).
NREL	National Renewable Energy Laboratory of the United States Department of Energy (DoE).
SUT	solar updraft tower. It is a solar system to produce electricity, and it has greenhouse-like solar heat collectors, a chimney-like tower, and wind turbines driven by heated air moving upward due to buoyancy rather than by the natural wind.
PV	photovoltaic or photovoltaics.
PV2	photovoltaic solar power system example with 234 solar panels arranged as 78 groups (racks) of three attached panels, and with enabled 2-axis solar tracking. Each solar panel has a standard power of 350 W; thus, the total power capacity is 81.900 kW. The panels can continuously change their angular direction to be facing the solar disc.
PVGIS	Photovoltaic Geographical Information System, a free web application for analyzing photovoltaic solar systems, by the European Commission Joint Research Center (JRC).
PVF	photovoltaic solar power system example with 3465 solar panels arranged as 7 lines (racks) of 495 connected solar panels, and with fixed orientation (no solar tracking of any kind). Each solar panel has a standard power of 350 W; thus, the total power capacity is 1212.750 kW. The solar panels' orientation is fixed such that they face south (azimuth = 0° or 180°, depending on the convention used) at an inclination angle of 25° from the horizontal (tilt = 25°).

PVH	photovoltaic solar power system example with 3465 solar panels arranged as 7 lines (racks) of 495 connected solar panels, and with enabled 1-axis solar tracking for the solar panels, permitting rotation about a horizontal axis. Each solar panel has a standard power of 350 W; thus, the total power capacity is 1212.750 kW. The solar panels face south (azimuth = 0° or 180°, depending on the convention used) here, but their slope is dynamically adjusted for maximum exposure to the incoming solar radiation. Such system can be viewed as a slightly modified version of the PVF system by just adding one rotational degree of freedom for each rack while keeping the layout the same.
PVV	photovoltaic solar power system example with 234 solar panels arranged as 78 groups (racks) of 3 attached panels, and with enabled 1-axis solar tracking for the solar panels, permitting rotation about a vertical axis only. Each solar panel has a standard power of 350 W; thus, the total power capacity is 81.900 kW. The solar panels maintain an inclination angle of 49° from the horizontal (tilt = 49°) while rotating about a vertical axis to follow the sun from east to west during the day.
PVWatts	also called PVWatts Calculator, a free web application for analyzing photovoltaic solar systems, by the National Renewable Energy Laboratory (NREL), of the United States Department of Energy (DoE).
TWh	terawatt-hour (10^{12} watt-hours).
W	watt.

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