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PV SIMULATION SOFTWARE COMPARISONS: PVSYST, NREL SAM AND PVLIB

T. Gurupira* and A.J. Rix†

* Department of Electrical and Electronic Engineering, University of Stellenbosch, Private Bag XI, Matieland, 7602, South Africa E-mail: tafadzwalgurupira@gmail.com

† Department of Electrical and Electronic Engineering, University of Stellenbosch, Private Bag XI, Matieland, 7602, South Africa E-mail: rix@sun.ac.za

Abstract: In this paper, three commercially available photovoltaic (PV) system simulation software programs are described and evaluated. The three, namely PVSyst, SAM and PVLlib, are assessed according to several criteria to identify their merits and demerits in different PV system modelling stages and scenarios. The work was inspired by the fact that there is quite a wide range of software programs available for simulating solar PV systems. Because each PV software simulator is created with specific desired goals, the programs tend to exhibit certain desirable features for some tasks and weaknesses in tackling other problems. As part of the evaluation, PVSyst, SAM and PVLlib were also used to model a 75MWp plant at Kalkbult in the Northern Cape Province of South Africa and their results were compared to the total yield produced by the plant in the year 2014. In the end, SAM was identified as potentially the most appropriate software for our future work. SAM not only modelled the 75MWp plant with considerable accuracy, but it also demonstrated several features that make it the most suitable of the three programs, for the next stage in our work involving the use of optimisation algorithms. This paper should also prove helpful to other users when choosing a PV simulation software program for a particular task out of the ones discussed herein.

Key words: simulation, software, PVSyst, SAM, PVLlib, performance, photovoltaic (PV) system.

1. INTRODUCTION

Solar power, in particular photovoltaics (PV), has been noted to be one of the fastest growing sources of electricity globally. This is mostly because solar energy is abundant, inexhaustible, clean, free and low maintenance, unlike its non-renewable counterparts such as fossil fuels. As the adoption of PV continues to increase, PV systems need to improve in terms of technological maturity and affordability in order to maintain the balance between electricity supply and demand [1]. One way to achieve this improvement is through forecasting. Forecasting is the use of performance models to estimate the expected energy output of a given PV system. The use of simulation software packages is a popular technique for forecasting as it not only allows users to model but also to analyse PV systems and their yields. During simulations, performance models use the PV system's design, orientation, weather data and location to predict the energy yield for a given period of time.

Currently, there are quite a number of solar PV simulation software packages to choose from. Different software packages have different features that make them more suitable for certain tasks than others [2]. This paper will focus on three of those packages, namely System Advisor Model (SAM), Photovoltaic systems (PVSyst) and PVLlib. In the following sections the three packages will be discussed in more detail and their respective merits and demerits will be examined according to certain qualification criteria.

2. SUMMARY OF THE SOFTWARE PROGRAMS

In this section SAM, PVSyst and PVLlib are described in more detail. For each program, a brief overview of its origins and main purposes as well as a general outline of a basic simulation will be given.

2.1 System Advisor Model (SAM)

SAM is a software package developed by the National Renewable Energy Laboratory (NREL) in the United States of America. SAM was originally called the Solar Advisor Model, but has since expanded its focus to also cover non-solar technologies such as geothermal power, wind power and biomass power, hence the name change. It is categorised as a financial and performance modelling software because it helps assess the operation of a proposed or actual renewable energy system and ties that in with an evaluation of the costs thereof. A typical SAM simulation consists of the following basic steps:

1. Selecting, from the interface, the required renewable energy technology and financing option.
2. Selecting the appropriate set of simulation and financing models. This is done by SAM in the background, based on the options selected in Step 1.
3. Specifying the necessary input variables such as the weather data file, site location and equipment. The supported weather files are typical meteorological year files (TMY2 or TMY3) and energy plus weather files (EPW).

4. Running the simulation. For advanced analyses, the user can configure simulations for sensitivity or optimization before running the simulations. The user can then view the simulation results on a variety of graphs and reports generated automatically by SAM in the user interface's results section. There is also an option to export the results to a third-party software package for presentation or further analysis.

SAM's features allows it to cater to the needs of a variety of users including project developers, engineers, manufacturers, academic researchers, technology developers and policy makers and analysts [3].

2.2 Photovoltaic Systems (PVSyst)

PVSyst is a PV-centric simulation tool that was originally developed at the University of Geneva but is now a standalone company. The software package focuses on modelling, sizing, simulating and analysing PV systems. PVSyst does have some sort of financial modelling in place, but it is primarily a performance modelling software [4].

A typical simulation in PVSyst consists of the following steps:

1. Defining the project. This is where the user creates the desired project on the user interface, names it and selects the corresponding geographic location and meteo file to be used. A number of sites and meteo files are already included in the PVSyst databases but the user also has the option of importing his own. PVSyst supports several types of weather files such as TMY2, TMY3 and EPW and files from sources such as Meteonorm, Photovoltaic Geographical Information System (PVGIS), World Radiation Data Centre (WRDC), Retscreen, Helioclim and SolarGIS.
2. Creating a system variant. This is where the user creates a calculation version of the project created in step 1. On the interface, the user gets to define various input parameters such as module orientation, system configuration and loss parameters.
3. Running the simulation. The user runs the simulation and generates a variety of graphs and reports for the analysis of the PV system. PVSyst allows the user to analyse the results in the program, export them to a different program or save the variant for further evaluation.

PVSyst offers the users extensive reports and breakdowns and valuable insights into the engineering aspects of design and deployment. This allows PVSyst to cater for a wide range of users including researchers and architects. Its interface is also multilingual and available in other languages such as German, French, Spanish and Italian, in addition to English [4].

2.3 PVLlib

PVLlib is a product of the collaborative efforts of a group of PV professionals called the PV Performance Modelling Collaborative (PVP MC), facilitated by Sandia National Laboratories in the USA. The PVLlib toolbox is a standard repository for PV system modelling and analysis algorithms [5]. To date, it does not have any financial models implemented so it is only a performance modelling software package. The PVLlib toolbox uses code-level modular programming to perform the modelling of the system. The toolbox is available in MATLAB or python programming languages. The PVLlib toolboxes do not come with any graphical user interfaces so the user is expected to call the functions, set the required parameters and execute the simulation using the modules provided as building blocks. A typical simulation in PVLlib comprises the following steps:

1. Setting up the location and design of the PV system. This includes importing the necessary python libraries and add-ons, collecting the weather data for the desired site and setting the orientation of the PV modules or arrays. The weather data is obtained from typical meteorological year files (TMY2 and TMY3).
2. Modelling the DC (direct current) IV (current-voltage) characteristics. This entails the estimation of the chosen module's behaviour according to its IV characteristics given in the module database, in response to the weather data given in step 1. Along with some intermediate results, the user obtains the estimated DC power yield.
3. Converting the DC power to AC (alternating current). The user makes use of a PVLlib module that takes in the technical characteristics of a desired inverter as one of the parameters and models the AC power output.
4. Plotting the graphs and tables. The user also has the option of exporting the simulation results for presentation or further analysis in a third-party software package.

Access to PVLlib is free and the software itself is easy to install. Its code is open-source and therefore transparent and easy to edit or modify [6]. The modular approach in PVLlib allows users to draw better analyses on portions of the modelling chain separately. Because of the programming literacy that PVLlib requires, the program attracts users mostly from specialised fields such as engineering and research.

3. COMPARISON OF THE SOFTWARE PACKAGES

SAM, PVSyst and PVLlib were compared to each other according to various evaluation criteria. Amongst other considerations, previous investigations into software packages available on the market [2, 7, 8] and future work

that will depend on the software package choice were all used in the decision making process to come up with the final list of the evaluation criteria. The final list was as follows:

1. Cost and commercial availability
2. Working platforms
3. Updatability
4. User-friendliness and ease of use
5. Reporting and analysis options
6. Modelling flexibility
7. Performance and economic modelling capability
8. Validation of simulation results with field data

3.1 Cost and commercial availability

SAM and PVLlib are free to download but you need a registration key to activate your copy of SAM. NREL provides SAM registration keys free of charge and uses your registration data merely for statistical purposes [3].

As for PVSyst, after installing it users can use it for free in the evaluation mode for 30 days during which it runs at full capacity. To enjoy the full capabilities thereafter, a user will have to purchase a license, otherwise PVSyst will automatically switch to its demo mode in which it runs with limited capabilities. The licensed mode is available in two flavours, namely Pro30, for PV systems up to 30kW and Premium, the more expensive one which works with unlimited sizes of PV systems. A full listing of the prices for the licenses can be accessed on the PVSyst website [4]. PVSyst also supports academics with discounts on licenses bought for educational purposes. The discounts are available for schools, universities and other educational institutes on request directly from PVSyst.

3.2 Working platforms

PVSyst runs only on Windows client versions currently supported by Microsoft. The supported versions are Vista, 7, 8 and 10 on both 32 and 64 bit systems. Other operating systems are supported through the use of virtual machines running Windows such as VirtualBox [4].

SAM runs on Windows 7, 8 and 10 and is available in both 32 and 64 bit versions. SAM also runs on OSX and Linux operating systems but is only available in 64-bit versions [3].

PVLlib comes in two different types of toolboxes, namely PVLlib for MATLAB and PVLlib-python [6]. As the names suggest, the two toolboxes work on MATLAB and python environments respectively. PVLlib-python works on platforms that have python versions 2.7, 3.4 or 3.5 and Pandas versions 0.13.1 or newer and these versions of

python are available for Windows, Mac OS X and Linux [9]. MATLAB is also supported on Windows, Mac OS X and Linux.

3.3 Updatability

To date, PVSyst has had 10 updates in this year alone- version 6.40 to version 6.49. The PVSyst website provides information with regards to the improvements and fixed errors associated with each update and the date each update was released [10].

SAM, currently on version 2016.3.14 revision 4, has had up to 5 revisions and updates this year alone. As is the case with PVSyst, the NREL SAM website shows release notes for each of the updates and revisions, highlighting the improvements made and errors fixed [11].

PVLlib has also had quite a few updates to date. This year alone there have been six updates so far, with the latest one, version 0.4.1, having been released on the 6th of October 2016. All the releases are available on GitHub and are accompanied by a brief summary of the associated bug fixes, version documentation and acknowledgements of main contributors [12].

3.4 User-friendliness and ease of use

SAM comes with a graphical user interface (GUI). This makes it easy for users with no experience in computer programming or developing computer models to build PV systems and perform simulations. The GUI allows users to find their way around the program with relative ease. It provides access to input variables and simulation controls and it displays the user's selections as well as graphs and tables after running the simulation.

PVSyst also has a graphical user interface (GUI) that makes it possible for users who are not particularly experienced in computer modelling to build their own PV systems, perform basic simulations and generally navigate their way through the software program with relative ease. The interface in PVSyst allows the user to perform system designing and sizing and to obtain results in graphical or tabular form easily. For most of the tasks, the user only has to input certain required values in the appropriate fields and then execute actions by the touch of a button.

PVLlib does not offer a graphical user interface. It is essentially a collection of scripts and functions that handles data, module and inverter parameters and takes in atmospheric and irradiance models. The user runs these scripts and functions sequentially to perform PV system simulations. The interface is therefore bound to present some challenges to users with no programming skills or experience in computer modelling of PV systems.

3.5 Reporting and analysis options

SAM has a default graphing tool that not only enables the display of results as sets of default graphs but also allows

the creation of custom graphs. Alternatively, the results can be presented in the form of tables or exported to other software packages for presentation or further analysis. SAM also provides a number of options for simulation results analysis, namely [13]:

1. Parametric analysis - This enables the user to assign multiple values to input variables in order to create graphs showing the relationship between one or more input variables to a metric result. This operation is ideal for the optimization of input variables.
2. Sensitivity analysis - This option enables a user to investigate how sensitive an output metric is to variations in certain input variables.
3. Statistical analysis - This analysis option allows the user to investigate uncertainties in one or more input variables on output metrics.
4. Multi-level subsystems - This allows users to model power systems as a combination of subsystems. This could be ideal, for instance, in a situation where each subsystem is meant to be oriented in a different direction.
5. Excel Exchange - This option allows the user to link an input variable in SAM to a cell or range of cells in a Microsoft Excel Workbook.
6. P50/P90 analysis - This is a method of calculating the probability that a system's total annual output will exceed a certain value, for a site of which the weather data is available for many years.
7. Exchange Variables - This option allows the user to input his own variables for use with a custom Transient System Simulation (TRNSYS) deck or Excel Exchange.

PVSyst, like SAM, documents simulation results into reports, summarising the simulation parameters, main results and system quality. The results can also be viewed as tables or exported to a third party software package like Microsoft Excel for further analysis or presentation. The only analysis option that PVSyst offers is the P50/P90 [4].

PVLib allows the user to view simulation results by plotting the respective metric's graph or exporting the results to a third-party software package such as Microsoft Excel for further analysis. The original PVLib toolbox does not offer any analysis options.

3.6 Modelling flexibility

PVSyst comes as a complete desktop application and does not have an allowance for scripting. That means that the user can only model a PV system the design of which adheres to certain predefined standards in PVSyst. It is therefore not possible for the user to introduce or modify

any of the thermal, electrical or optical models in PVSyst [14]. Users can however define devices not found in the PVSyst component databases using the manufacturers' datasheets, thereby creating new devices in the database.

SAM also comes as a complete desktop application but it has a built-in scripting language, SAM User Language (SamUL). This allows the user to automate tasks and to perform more complex analyses from within SAM [3]. With SAM, a user also cannot introduce new thermal, electrical or optical models but can link and import variables from other other programs such as Microsoft Excel and TRNSYS. The user is also allowed to define devices that cannot be found in the component database using the component's datasheet.

PVLib is built on the very basis of modelling flexibility. The availability and free access to the PVLib source code makes it possible and easy for users to modify models, databases and input methods for a range of research and design goals [5, 6].

3.7 Performance and economic modelling capability

SAM has a lot of performance models for photovoltaic systems, concentrating solar power, solar water heating, wind power, geothermal and biomass power. The photovoltaic systems in SAM are further subdivided into three categories:

1. Flat Plate PV, which models the system using sub-models for the components (modules and Inverters) of the system. This is the model we will use for our grid-connected PV system performance model.
2. High-X Concentrating PV, which models concentrating photovoltaic (CPV) systems.
3. PVWatts, which models crystalline silicon-based systems and is an implementation of NREL's PVWatts model which is web-based.

SAM offers a significant number of financial models. The models calculate the cash-flows and financial metrics for different financing options chosen by the user. The financial models given in SAM are for residential projects, commercial (excluding Commercial PPA) projects, commercial projects with power purchase agreements (PPA) and utility projects [3].

PVSyst only deals with photovoltaics and it splits its performance models into four main categories:

1. Grid-connected - This is a type of system that is made up of components constituting the PV array i.e. modules/ strings of them, inverters and everything up to the connection to the grid.
2. Stand-alone - A system which should constitute of modules, a battery and a regulator.

3. A water pumping system.
4. DC Grid - A system made up of a PV-array and a load profile meant for public transport network.

PVSyst also offers economic evaluation to model project costs and investments. With the financial model, the user can project running costs and deduce the long-term profitability, especially for grid-connected systems [4].

The PVLib original toolbox has a performance model that currently only supports grid-connected systems and does not offer any financial models. There is, however, room for improvement in PVLib and for more experienced users to expand on PVLib's capabilities and add elements that will help them model other systems [5, 6, 15].

3.8 Comparisons of Simulation results

A site at Kalkbult in the Northern Cape Province of South Africa was selected for simulation. It is a 75MWp solar PV plant made up of 84 sub-systems, each containing 3720 polycrystalline modules and an inverter. The configuration is such that there are 24 series modules per string and 155 parallel strings feeding into each of the 84 inverters. The entire system therefore consists of 312 480 modules over a total module area of 516 217m² and 84 inverters. Figure 1 is an aerial view of the plant at Kalkbult and Table 1 summarises the configuration of the subsystems. Table 2 lists the PV system's losses as sourced from the actual plant.



Figure 1: Aerial view of the 75MWp plant at Kalkbult. Photograph Courtesy of Eric Miller, Scatec Solar [16]

The 75MWp solar plant was modelled in the three programs to simulate the total energy yield for the whole year using the Hay irradiance model. Weather data measured on the site for the year 2014 was used in the simulations and the simulated total energy yield of each software package was compared to the total yield recorded at Kalkbult for the year 2014.

Table 3 is a summary of the total yield produced by the simulations in each of the software programs and their

Table 1: Sub-system configuration

Variable	Description
Module orientation	0°, facing North
Inclination	30°
Type of installation	free-standing
PV module model	BYD P6-30, 240 W
Inverter model	SMA Sunny Central 800CP

percentage differences from the actual plant yield. In Figure 2, the three simulated annual yields are compared to the plant's actual yield for the year 2014 and in Figure 3, a similar comparison is drawn based on the energy profiles on randomly selected clear sky and cloudy days. The results show that PVSyst simulated the yield more accurately, with a calculated percentage difference of 3.4%, followed by SAM with 3.9% and then lastly PVLib with approximately 5.1%. The percentage difference was calculated as:

$$Difference(\%) = \frac{Yield_{actual} - Yield_{simulated}}{Yield_{actual}} \cdot 100\% \quad (1)$$

All three software programs were generally conservative in their yield predictions mostly because of the overestimation of losses in some of the programs' default loss models. This is especially true in the cases of PVSyst and SAM simulations where the actual losses at Kalkbult were overestimated by the default loss models

Table 2: Summary of plant losses

Loss	Value (%)
Shading	-2.5
Reflection	-2.5
PV loss due to irradiance level	-0.45
Module mismatch and DC ohmic	-1.77
Soiling loss	-1.75
PV loss due to temperature	-6.3
Inverter loss	-2.6

Table 3: 2014 Total Yield Comparison

Source	Total Yield (MWh)	Difference (%)
Actual yield	149868.2	-
PVSyst	144813.6	3.37
SAM	144046.4	3.86
PVLib	142276.8	5.07

4. CONCLUSIONS

Analysis of the software packages revealed that each software package has its own merits that makes it more suitable than the others for certain simulations, and demerits that serve as disadvantages in certain instances. In terms of accuracy and robustness, PVSyst seemed to outperform the rest, closely followed by SAM. In terms of modelling flexibility, PVLib was the best, again closely

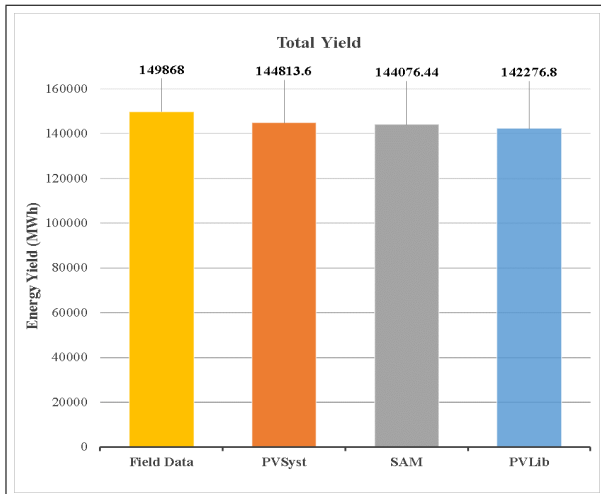


Figure 2: Total energy yield for the year 2014

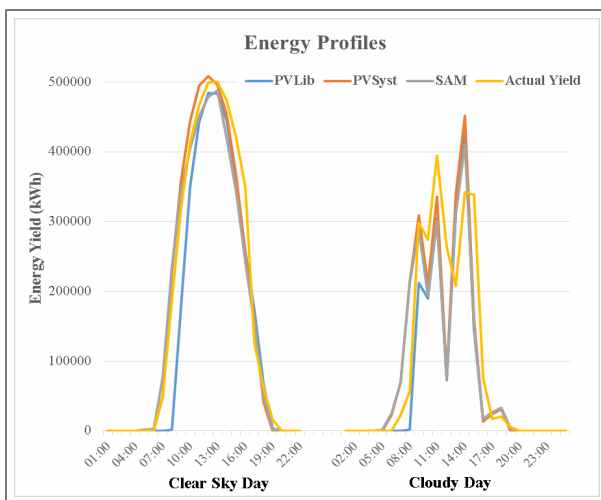


Figure 3: Clear sky and cloudy day energy profiles

followed by SAM. In terms of other general characteristics and functionalities, it seems SAM will be the most suitable of the three software packages evaluated in this paper for our future work. SAM proved to be a fairly accurate, complete, free, easy to install and user-friendly solar PV simulation tool that also comes with a fair amount of modelling flexibility and has a wide range of reporting and analysis options which will potentially come in handy in the implementation of optimisation algorithms in our future tasks.

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