



World-wide overview of design and simulation tools for hybrid PV systems

PVPS

**PHOTOVOLTAIC
POWER SYSTEMS
PROGRAMME**

Report IEA-PVPS T11- 01:2011

International Energy Agency
Photovoltaic Power Systems Program

**World-wide overview of design and simulation tools
for hybrid PV systems**

IEA PVPS Task 11

Report IEA-PVPS T11-01:2011

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1. Foreword

The International Energy Agency (IEA), founded in November 1974, is an autonomous body within the framework of the Organization for Economic Cooperation and Development (OECD) which carries out a comprehensive program of energy co-operation among its member countries. The European Commission also participates in the work of the IEA.

The IEA Photovoltaic Power Systems Program (PVPS) is one of the collaborative R&D Agreements established within the IEA. Since 1993, the PVPS participants have been conducting a variety of joint projects in the application of photovoltaic conversion of solar energy into electricity. The mission of the IEA PVPS program is: *To enhance the international collaboration efforts which accelerate the development and deployment of photovoltaic solar energy as a significant and sustainable renewable energy option.*

The IEA PVPS Program aims to realize the above mission by adopting four objectives related to reliable PV power system applications for the target groups of governments, electricity utilities, energy service providers and other public and private users.

1. To stimulate activities that will lead to a cost reduction of PV power systems applications.
2. To increase the awareness of PV power systems' potential and value and thereby provide advice to decision makers from government, utilities and international organizations.
3. To foster the removal of technical and non-technical barriers of PV power systems for the emerging applications in OECD countries.
4. To enhance co-operation with non-OECD countries and address both technical and non-technical issues of PV applications in those countries.

The overall program is headed by an Executive Committee composed of one representative from each participating country, while the management of individual

research projects (Tasks) is the responsibility of Operating Agents. By mid 2010, thirteen Tasks were established within the PVPS program.

The overall goal of Task 11: “PV Hybrid Systems within Mini-grids” is to promote the role of PV technology as a technically relevant and competitive source in mini-grids. It aims at enhancing the knowledge-base of multi-source power generation systems including PV and associated electric distribution networks. The objectives of the Task are to:

- define concepts for sustainable PV hybrid mini-grids taking into account local factors (specificity of the application, financing regimes, location, others);
- provide recommendations on individual designs (mix of technologies, architecture, size, performances, other) in order to achieve high penetration level of PV as a mean to improve quality, reliability and economics of electrification systems such as mini-grids;
- assess the potential of technologies to be mixed with PV for hybridisation; and,
- compile and disseminate best-practices on PV hybrid power systems.

The current members of the IEA PVPS Task 11 are:

Australia, Austria, Canada, China, France, Germany, Italy, Japan, Malaysia, Spain, and United States of America.

This report concentrates on software design and simulation tools for PV hybrid systems. The tools are classified as to their capability and their application in the design process. A survey of existing software tools provides summary information on the availability, features, and application of commonly used tools. Ten representative software tools are reviewed in more detail. Guidelines and recommendations on the use of software tools for PV hybrid design are presented. The technical report has been prepared under the supervision of PVPS Task 11 by:

Luis Arribas from Ciemat, Madrid, Spain, Georg Bopp and Matthias Vetter from Fraunhofer Institute for Solar Energy Systems ISE, Freiburg, Germany, Anja Lippkau from Conergy AG, Hamburg, Germany and Konrad Mauch, Operating Agent, Gabriola Island, Canada.

The report expresses, as nearly as possible, the international consensus of opinion of the Task 11 experts on the subject dealt with. Further information on the activities and results of the Task, and the Task's other published reports, can be found at: <http://www.iea-pvps-task11.org> and <http://www.iea-pvps.org>.

2. Executive Summary

The International Energy Agency Photovoltaic Power System Executive Committee has launched the Task 11: “PV Hybrid Systems within Mini-grids” for the period 2006-2011. This Task builds on the work on PV hybrid systems undertaken in PVPS Task 3 and currently includes participants from 11 IEA countries. Reports resulting from Task 11 activities are available on the IEA PVPS web-site - <http://www.iea-pvps.org> . Activity 12 inside the IEA Task 11 deals with the evaluation and comparison of system design methodologies and tools and development of guidelines for design tools.

Off-grid PV systems and, in particular, hybrid PV systems are characterised by a high degree of complexity at the dimensioning stage. For this reason, as in many other fields, software simulation is an important aid. There is already a broad diversity of such programs on the market. To get a world-wide overview of the available software tools and their features, a survey was initiated among Task 11 participants to learn about the tools they use.

The survey questionnaire and subsequent analysis dealt with

- licensing policy (e.g. open-source, freeware, shareware, commercial),
- cost (e.g. free, one-time purchase, annual license or maintenance fees),
- availability (downloadable, available by order, internal use only),
- features (e.g. available models, analysis and simulation capability, software platform),
- application area (e.g. feasibility analysis; system dimensioning; simulation and research), and
- characteristics and quality of user interface and documentation.

Results were obtained for 23 software tools. The analysis also included two well-known tools which were not reported by the Task 11 experts. In addition to tools

focused on PV hybrid systems, the survey also gathered information on tools for the design of distribution networks for mini-grids.

The software tools can be divided into four groups:

1. dimensioning tools, which calculate the system dimensions on the basis of input data (load and climate data and system components),
2. simulation tools, which use the input data (load and climate data, system components and configuration) to simulate the behaviour of the system over a given period,
3. research tools with a high degree of flexibility and configurability to allow very complete simulation of different systems for research purposes, and
4. mini-grid design tools, which assist with the design of the mini-grid electrical distribution network.

Current software tools can greatly simplify and shorten the design process for PV hybrid systems. Several high quality tools are available at no cost. However they do have limitations. In order to maintain ease of use and limit complexity, dimensioning tools like RETScreen and PV*SOL usually limit the available options for energy sources, system architectures, and dispatch strategies. Simulation tools such as HOMER and Hybrid2 allow very detailed analyses. Both allow the inclusion of wind turbines in the system analysis. Only HOMER allows comparison between DC and AC coupled systems.

The research tools, such as TRNSYS and INSEL, and the standard commercial system simulators, such as MATLAB and Dymola, allow much more flexibility in defining energy sources, system architectures, and dispatch strategies, but at the expense of considerably more effort to learn the software and develop the models. For the standard commercial system simulators, with the exception of Simplorer, the models for PV and renewable energy components must be developed by the user, or obtained through cooperation with research institutions that have developed proprietary models.

A limitation is that no direct data exchange is possible among the programs. This must be done by using (or developing) an auxiliary program or with paper, pencil and manual input.

One of the key decisions to be made by the user when selecting a software tool concerns the desired focus of the calculations: preliminary feasibility study and general dimensioning (RETScreen), economic considerations (HOMER), a detailed technical configuration (PV-SPS, PV*SOL, PVsyst), system analysis (Hybrid2, PV-DesignPro) or detailed research (TRNSYS, MATLAB/Simulink).

In conclusion, it must be pointed out that the results of the system design and system simulation are dependent not only on the calculation algorithms of the program concerned, but also to a high extent on the quality of the input data, i.e. the technical knowledge and experience of the program user. The software will prove a very useful aid during the process of system identification. The output results, however, should always be appraised with the due critical objectivity!

The final outcome of the survey is a report that provides an overview of available software tools, their features and guidelines for the selection and use of the tools for particular applications.

3. Introduction, scope and objective

Off-grid PV systems and, in particular, hybrid systems are characterised by a high degree of complexity at the dimensioning stage, where energy sources and energy storage systems must be sized to match estimated energy needs and the expected availability of solar radiation. For this reason, as in many similar fields, software design and simulation tools are an important aid. There is already a broad diversity of such programs on the market. Some are very comprehensive and perform their calculations down to a very detailed level, whereas others are rather more suited for fast »coarse dimensioning«. The various programs integrate different sets of technologies (PV, wind, additional generators, etc.) and some also include economic calculations. The costs of the software tools, in terms of initial purchase price, ongoing maintenance costs, and the time required to learn how to use the tool, also vary significantly. These differences often make it difficult to select the best package for the task at hand.

To provide guidance for the selection and use of these software design tools, a survey was initiated among Task 11 Experts to get an overview of existing software tools for PV hybrid system design and simulation. The survey results were combined with data from a recent diploma thesis [1], [2] that examined several design tools in detail, and data from an earlier paper on design and simulation tools for PV hybrid systems [3]. The initial results were presented at a workshop held at the European PV Conference in Valencia, Spain during September 2008 which brought together developers of design tools and users from industry, research institutes and academic institutions [4]. The discussions and presentations at the workshop provided more insight into the current status and future development of the most popular tools and provided the basis for many of the recommendations in this report.

If expert users need more specific information concerning the component models used in these tools, especially for the PV generator, reference to a recent report from Sandia National Laboratories is recommended [5].

4. Types of Tools

To assist in evaluating the wide range of available tools, they are classified into four categories: dimensioning, simulation, research and mini-grid design tools.

4.1. Dimensioning (Dim) tools:

A dimensioning tool (also referred to as a sizing tool) performs dimensioning of the system: given an energy requirement, it determines the optimal size of each of the different components of the system. Different tools may optimise for different objectives. Some will attempt to explicitly minimise the life-cycle cost of the system, while others may size the system according to rules that, it is assumed, lead to a properly functioning system. Most sizing tools provide detailed information about energy flows among components and indications of the critical periods during the year.

Sizing tools are usually small, compiled software packages. They generally have a user interface designed to be quick and easy to use. Sizing tools are the type of software most often used by system installers.

4.2. Simulation (Sim) tools:

With simulation tools, as opposed to dimensioning tools, the user must specify the nature and size of each component. The tool then provides a detailed analysis of the behaviour of the system. The time resolution of the simulation (i.e., the length of the time step), varies among simulation packages and depends on the level of detail required and the availability of input data (e.g., weather data). Hourly simulations, which are common, can be used to verify system sizing, investigate the impact of future changes in the load, look at performance under atypical conditions (e.g., worst-case weather), investigate the sensitivity of the design to various parameters, or analyse the impact of the failure or deterioration of the components. Simulations can also provide information concerning the financial and environmental characteristics of the system, such as the life-cycle cost and CO₂ emissions.

Simulation tools can also be used for sizing. This requires that the user correctly identify the key variables and then repeatedly run the simulation, adjusting the variables manually to converge on an acceptable sizing. Some packages automate this process.

Simulation tools are usually compiled software distributed by research centres and specialized companies.

4.3. Research tools:

Performing R&D at component and systems level requires a high level of flexibility in the interaction of the components. While traditional simulation tools can perform extensive sensitivity analyses, they generally do not permit the user to modify the algorithms that determine the behaviour and interactions of the individual components. For this, an open architecture is required: the software consists of a selection of "routines", describing the components, and platform for linking these routines together. The user is at liberty to modify the routines or add wholly new routines. Such research tools can be either implemented within a commercially available, general-purpose simulation environment, or programmed and compiled in a language such as Fortran, C or Pascal.

The flexibility and power of open architecture research tools make them the tools of choice of research organisations; their inherent complexity limits their usefulness for commercial system analysis, sizing and design. A subset of the routines in the tool can usually be compiled and distributed commercially, however. The result is typically a traditional sizing or simulation tool.

4.4. Mini-Grid Design tools:

Mini-grid design tools assist with the design of the mini-grid electrical distribution network. Specialized tools are available that, for example, allow the designer to determine if a stand-alone solar home system or a connection to the centralized PV system is the more cost effective solution for a single house in a village. Another tool

allows the designer to minimize the power losses in the distribution network with a proper selection of voltage level and cross section of the distribution cables. General purpose distribution system design tools oriented towards utility-scale applications can also be used if they have the capability to model multiple generation sources within the distribution network.

Task 11 has not assessed these types of programs for suitability in mini-grid design. However Sandia National Laboratories in the USA has assessed the ability of current distribution system simulation tools to deal with high penetration of renewable resources in conventional distribution systems [6]. This assessment should also be applicable to mini-grids.

5. Overview of Design and Simulation Tools

The survey sent to Task 11 Experts asked them to respond with information about software tools that they used or that they knew were being used by other experts.

The survey questionnaire and its subsequent analysis dealt with:

- licensing policy (e.g. open-source, freeware, shareware, commercial),
- cost (e.g. free, one-time purchase, annual license or maintenance fees),
- availability (downloadable, available by order, internal use only),
- features (e.g. available models, analysis and simulation capability, software platform),
- application area (e.g. feasibility analysis; system dimensioning; simulation and research), and
- characteristics and quality of user interface and documentation.

Results were obtained for 23 software tools as shown in Table 1. In this table the tools are arranged according to their availability: free (can be downloaded from the internet without fee), commercial (a fee is necessary), standard commercial system simulators (require purchase of the simulator package and development of models to meet the specific needs of the analysis desired), and internal (only available inside a specific organisation or company).

Table 1 - Overview and availability of simulation tools based on survey results

(dim: dimensioning tool, des: mini-grid design tool, sim: simulation tool, res: research tool)

free tools		standard commercial system simulators		
RETScreen	dim	Simplorer (APL)		
HOMER	sim/dim	PowerSim	res	
Hybrid2	sim	MATLAB/Simulink	res	
Vipor *	des	Dymola	res	
Jpélec *	des	PowerFactory	res	
* Mini grid design		internal tools		
commercial tools		Off Grid Sizer	dim	Conergy
Off Grid Pro	dim	Sunny Island Design	dim	SMA
PVsyst	sim/dim	PVS	sim/dim	ISE
PV*SOL	sim/dim	TALCO	res	ISE
Solar Pro	sim	Dymola	res	ISE
		MATLAB/Simulink PVToolbox	res	Canmet
		MATLAB/Simulink Hysis	res	CIEMAT
		MATLAB/Simulink N.N.	res	ISET
		PowerFactory Tool box	res	ISET

In addition to the IEA Task 11 survey, Suntechnics (DEU) and Fraunhofer ISE (DEU) sponsored a diploma thesis [1] on PV hybrid design tools at the FHTW Berlin (University of Applied Sciences) in 2006. The task was to analyse those programs that are generally available which are specifically able to model hybrid systems (PV-diesel-batteries) and which appear to promise a short familiarisation period. The results are a more detailed evaluation (compared to the Task 11 survey) of seven selected simulation programs, see Table 2, which are relatively well known and for which the familiarisation process is relatively easy [2].

The evaluation summarized in Table 2 assessed the 7 programs according to the following criteria:

- Instruction manual quality – rating based on the scope of information given, the clarity of presentation and the ease of understanding for the user.
- User-friendliness - rating based on evaluation of the structure and intuitive nature of the user interface, and the number of input steps necessary to reach a chosen program function.

- Component dimensioning - whether, and for which components, this function is available.
- Simulation capability - whether, and for which components, this function is available.
- Plausibility check – availability of a function to check the technical feasibility of specified configurations and issue warnings in case of discrepancies.
- Irradiation database - whether such a database exists, and whether it is possible to perform shadowing analyses.
- Emission balance – availability of a function to calculate the emissions of various gases with negative climate effects and the pollutant savings achieved by renewable energy generation.
- Economic analyses – availability of investment and operating cost calculations over a given period.
- Clarity of data input - considered separately for user design input and addition of new system components to the component database. The assessment of the two input procedures considers the clarity of the input form layout and the effort required to enter a particular item of data. In the case of the system components, important factors were the integration of databases and the possibilities to expand these databases.
- Clarity of result presentation - assesses the layout and variants for result presentation (e.g. graph, table, scatter plot). The time resolution of the results is given and the scope and presentation of the project reports and print-outs is evaluated.

Table 2 - Overview of dimensioning and simulation programs for hybrid PV systems

(+ good/easy, o satisfactory, - sufficient/laborious, S shadowing analysis)

Software	Dimensioning (Dim)		Dim. + Sim.		Simulation(Sim)		
Program	PV-SPS	RETScreen	PV*SOL standalone	PVsyst	Hybrid2	PV-DesignPro	HOMER
Version evaluated/Origin	3.0/AUS	4/CAN	3.0/DEU	4.33/CHE	1,3c R3/USA	v6,0/USA	2.67 beta/USA
Date of evaluated version	2008	2008	2007	2008	2004	2008	2008
Date of 1.version	2001	1997	1998	1994	1998	1998	1993
Costs (single license)	99 (AUS \$)	free	348 Euro	900 (CHF)	free	259 US \$	free
Language versions	Engl.	30 Languages Engl., French, Chinese,....	Ger., French, Engl., Spain, Ital.	Ger., French, Engl., Spain, Ital.	Engl.	Engl.	Engl.
Instruction manual quality	(1)	+	+	detailed F1 man.	-	o	+
User background knowledge	normal	normal	normal	normal	high skilled	normal	skilled
User friendless	o	+	o	o	-	o	+
Component dimensioning(2)	PV-D-B	PV-D-B	PV-B	PV-B	no Dim.	no Dim.	(3)
Simulation (2)	no Sim.	no Sim.	PV-D-B	PV-D-B-P	PV-D-B-W	PV-D-B-W	PV-D-B-W-(+)
Plausibility check	yes	no	yes	yes	no	no	yes
Irradiation data base	4 locations	yes + NASA link + S	yes + S	yes + NASA link + S	yes	yes + S	yes + NASA link
Wind data base	no	yes	no	no	no	no	no
Emission balance	no	yes	yes	no	yes	no	yes
Economic analysis	no	yes	yes	yes	yes	yes	yes
Clarity of data input for users	o	+	-	o	-	-	+
Clarity of data input for system components	+ (4)	+ (5)	+	+	-	+	+
Clarity of result presentation	+	+	o	o	-	o	+
Time resolution of the output	month, year	month, year	hour, day, week, month, year	hour, day, month, year	User-defined	hour, day, week, month, year	hour, day, week, month, year
Project report/ printout	o	+	+	+	-	o	+

1) No separate manual, the tool should only be used in conjunction with the relevant Australian standards for off-grid-systems (AS 4509 Parts 1, 2 & 3 and AS 4086 Part 2)

2) PV = PV-generator; D = diesel-generator; B = battery; W = wind generator; P = water pump; (+) =further energy sources, e- g. biogas, fuel cell

3) If several components of different sizes are entered, all the possible combinations are simulated and combination proposals are listed on the basis of their economic viability.

4) No component database available

5) PV module database is not extendable by the user

6. Reviews of Specific Tools

The 7 programs listed in Table 2, plus the tool “Vipor” for the design of distribution networks for mini-grids and three research tools, “TRNSYS”, “INSEL” and “MATLAB/Simulink”, are reviewed here in more detail. Information has been derived from the Task 11 survey, the diploma thesis [1], web-sites of the tool developers, and presentations and discussion from the Valencia workshop [4]. Since software tools are regularly updated, readers are advised to check the web-sites listed below to learn about the capabilities of the latest version.

6.1. PV-SPS (Version 3.0)

PV-SPS (PV Stand-alone Power Systems) is a dimensioning program for PV-diesel off-grid systems based on Excel spreadsheets. It performs its calculations to the Australian industry standards and was developed by the Australian Business Council for Sustainable Energy (BCSE). It demands a certain level of prior knowledge for the specification of the loads and system components and is thus aimed above all at experienced users in the off-grid field. Furthermore, it is designed to be used in conjunction with the relevant Australian standards for off - grid systems (AS 4509 Parts 1, 2 & 3 and AS 4086 Part 2).

One special feature of PV-SPS is the distinction between summer and winter, for which two groups of loads (one for each season) need to be entered. In addition, regional factors are specified for each month for seasonal loads, alongside irradiation and temperature data for four different locations in Australia. The program outputs on the one hand three different PV generator sizes, based on the mean irradiation values of the best and poorest months, as well as the annual mean value, and on the other hand the size of a diesel generator corresponding to the selected system operating mode. Even though the layout of the individual input forms is not always optimal in terms of clarity, the two graphs presenting the monthly energy consumption and power generation give a good general impression of the system performance over the course of the year.

More information is available, and ordering of the software is possible, on the website: <http://www.cleanenergycouncil.org.au/cec/accreditation/Solar-PV-accreditation/forms.html> (accessed 11 January 2011).

6.2. RETScreen (Version 4)

This program, which is also based on Excel spreadsheets, was developed by the Canadian government (Ministry of Natural Resources) and supports basic dimensioning calculations for PV-diesel off-grid systems. RETScreen stands out by way of its fast and simple input, as databases are provided for PV modules and climate data for more than 6000 ground stations (month-by-month solar irradiation and temperature data for the year). Via a link to the NASA Internet site, climate data can also be retrieved for any chosen point on earth. Further components can only be defined with a limited scope of technical specifications, which means that the output configurations should best be treated as dimensioning guidelines. Economic viability and emissions calculations can be performed for the dimensioned system.

The program is offered in more than 30 languages and includes a wide variety of additional tools covering other renewable energy sources together with a comprehensive manual and a collection of case studies. It can be downloaded free of charge at the following website: <http://www.etscreen.net/ang/home.php> (accessed 11 January 2011).

6.3. PV*SOL Professional (Version 3)

PV*SOL, which was developed by Dr. Valentin, Energiesoftware GmbH in Berlin, Germany, is a time-step simulation program for off-grid and grid-coupled solar generation systems and is able to perform energy yield calculations, analysis of economic efficiency and analysis of the influences of shadowing. The program is available in different versions with varying capabilities.

Besides the full simulation over time, there is a »quick design« function for off-grid systems, though this is limited to dimensioning of the PV generator and storage battery (no additional diesel generator). The loads can be entered either in very fine detail (individual loads and their operating times) or by way of a general specification

of annual energy consumption and selection of a load curve. The »quick design« can be transferred into the simulation and supplemented accordingly (e.g. with an additional generator). Before the actual simulation is started, a plausibility check is performed and any inconsistencies are pointed out to the user. The simulation results are output in graph form (characteristic curves for specific parameters) or tables, with the possibility to output up to eight different variables at once. The system report (as a print-out or export file for further processing) comprises a system diagram, the most important technical data of the system and energy balances.

More information is available, and ordering of the latest version of the software (Version 4 as of January 2011) is possible, on the website: <http://www.valentin.de/> (accessed 11 January 2011)

6.4. PVsyst (Version 4.33)

This time-step simulation program, developed at the University of Geneva, Switzerland, is able to simulate both grid-coupled and off-grid systems (energy flow, shadowing and economic viability). It provides dimensioning proposals for stand-alone installations (PV generator and battery size), and warns the user if the chosen component combinations are not technically feasible. The dimensioning proposals are calculated on the basis of load inputs, specification of the number of days for autonomous operation and an estimation of the so-called »loss-of-load probability«, i.e. the duration for which the load cannot be served by the PV and battery energy.

As there are no inverter models for off-grid system simulation, it is only possible to model DC systems. The additional generator serves only to charge the batteries. The loads can be specified in various ways: individual inputs, load profile creation, probabilities of particular power values, data import and differentiation of individual periods. Comprehensive component databases are provided, permitting new components to be entered by way of typical technical data. The output options for the calculation results are similarly extensive and offer a wide range of presentation forms (e.g. characteristic curves of specific parameters, scatter plots, histograms, printed reports).

More information is available, and ordering of the latest version of the software (Version 5.31 as of January 2011) is possible, on the website:
<http://www.pvsyst.com/5.2/index.php> (accessed 11 January 2011).

6.5. Hybrid2 (Version 1.3c R3)

This pure simulation program, developed by the National Renewable Energy Laboratory (NREL) of the U.S. Department of Energy in cooperation with the University of Massachusetts, is one of the pioneer programs in the field. It was conceived for analyses of hybrid systems with several energy generators (PV, wind and diesel generators) and loads (AC, DC and thermal loads) and offers not only a broad spectrum of energy management strategy options, but also an economic analysis function. While the input forms are well structured, the output options fall short somewhat in terms of user-friendliness and clarity. Hybrid2 is especially popular in universities and colleges for research because it permits very comprehensive system analyses even though it requires some time for learning the software.

DOE/NREL stopped funding development about 5 years ago and it is now primarily supported by the University of Massachusetts. The Alaska state energy office has a strong interest in off grid power systems and has negotiated a 3 year contract for a major upgrade of the software with the University of Massachusetts. This will greatly improve the modularity of the code, improve the interface, change the software from a power base to an electrical base (volt and amp) and add components such as flywheels, hydrogen fuel cells and expanded battery life calculation.

Hybrid2 can be downloaded free of charge at the following website:
http://www.ceere.org/rerl/rerl_hybridpower.html.

6.6. PV-DesignPro (Version 6.0)

Developed by Maui Solar Energy Software Corporation in Hawaii, USA, this time-step simulation program is designed to simulate both grid-coupled and off-grid systems with PV and wind generators. The output of an additional generator (e.g. a diesel generator in a hybrid system) is constrained to match the shortfalls in

renewable energy, meaning that a realistic additional generator cannot be modelled. In addition to the energy balance calculations for dimensioning, the program also incorporates economic analysis, an optimisation tool, and a set of »sub-programs« which can be used to create load curves and to convert Meteororm climate data into the PV-DesignPro data format.

Alongside a quite comprehensive internal climate database with temperature, irradiation and wind data, component databases are also provided, including over 400 PV modules. Further PV modules, however, can only be entered by specifying technical data based on the Sandia PV array performance model [7].

More information is available, and ordering of the software is possible, on the website: <http://www.mauisolarsoftware.com/> (accessed 11 January 2011).

6.7. HOMER (Version 2.67 beta)

HOMER (Hybrid Optimisation Model for Electric Renewables) – another time-step simulation program developed by NREL – adds optimization to basic simulation capability. It simulates the annual performance of many different system configurations for a specified set of energy sources to find a configuration that satisfies technical constraints at the lowest life-cycle cost. It is also possible for the user to define sensitivities (e.g. different mean values for solar irradiation, wind or power consumption) to narrow the range of results. The outcome of the simulation is a list of the possible systems in order of life-cycle costs. A graph depicts the various ranges of the most cost-effective systems over the given operating period, based on the selected criteria. Detailed results can be output for each of the individual simulated systems (graphs, tables, scatter plot, print-out).

The program design is very user-friendly and incorporates not only PV, wind and small-scale hydro-generators, but also additional generators driven by a variety of fuels (e.g. diesel, bio mass, ethanol, hydrogen), and energy storage (both batteries and hydrogen). It is possible to connect the different sources and loads to either a DC or AC bus. However some expertise and attention is required to get valid results. For example, to get plausible values for the battery lifetime costs, a good understanding of battery lifetime behaviour and of HOMER's battery lifetime model is

necessary. Also, no check is made to determine whether the entered component combinations are technically feasible. For example, the PV generator is modelled simply by its peak output and not, as in other programs, as the combination of individual PV modules. Energy conversion efficiency is not considered for power converters used in the system. For example, no efficiency can be defined for the PV charge controller in a DC coupled system or for the PV inverter in an AC coupled system.

Despite these issues, which are important primarily when doing detailed system design, HOMER is a very convenient and widely used tool, especially where the economic aspects of a system are to be considered. HOMER is maintained by Homer Energy as of 2009 and version 2.68 of the program is available for free download at: <http://www.homerenergy.com/> (accessed 11 January 2011). The latest version is V2.80 and must be purchased.

6.8. ViPOR

ViPOR (Village Power Optimization for Renewables) is an optimization tool for designing village electrification systems which is developed by NREL. ViPOR decides which houses should be powered by isolated power systems (e.g. stand-alone solar home systems [SHS]) and which should be included in the village mini-grid. The mini-grid distribution network is optimally designed with consideration of local terrain.

To analyze costs and the proper layout of the distribution grid (e.g. length and diameter of cable), it is necessary to know the costs of cables, the relative costs of generating the electric energy by a centralized PV System and a solar home system and to have some data about the local geography. ViPOR requires a geographical description of the local terrain including the load points such as houses, schools, stores and health posts. It is possible to import geographic data from GIS database, a GPS survey, or a digitized map or simply enter the data by clicking with the mouse. To calculate the generating costs of PV electricity it is also possible to use HOMER as additional software that provides input for ViPOR.

The graphical user interface is user-friendly, but it is necessary to be skilled in village electrification, especially for setup costs. It is much easier to modify an existing example.

ViPORA is the only readily available tool for evaluating trade-offs between solar home systems or centralized PV mini-grids. It can be very useful for designing village electrification systems, but good information about local conditions is needed for good results. A limit of ViPORA is that it does not take power losses in the distribution network into account.

ViPORA is not as fully developed as HOMER, so it is recommended to use ViPORA closely with NREL. A pre-release version is available for free download from <http://analysis.nrel.gov/vipor> (accessed 11 January 2011)

6.9. TRNSYS

Available commercially since 1975, TRNSYS (abbreviation of “TRAnSient SYstems Simulation, pronounced "tran-sis") was initially developed for modelling of thermal energy flows in multiple zone systems. It is a transient system simulation program based on a modular architecture of Fortran code blocks. Hundreds of components are available, including PV arrays, charge controllers and weather generators. TRNSYS’s extensive use of Fortran generally requires that users be familiar with this programming language, at least at the development level. More information is available, and ordering is possible, at <http://www.trnsys.com> (accessed 12 January 2011)

6.10. INSEL

The program INSEL, which was initially developed for the simulation of hybrid PV systems by the University of Oldenburg, Germany, and is today supported by the South German company Doppelintegral GmbH is similar to TRNSYS and both include a comfortable graphical user interface. This means the users need not be familiar with the internal programming language and code, but they still have the option to develop and add their own models in Fortran or C. More information is available, and ordering is possible, at <http://www.inseldi.com> (accessed 12 January 2011).

6.11. MATLAB/Simulink and other general system simulators

MATLAB, developed by the MathWorks (www.Mathworks.com) in 1984 and subsequently upgraded several times, is a technical computing environment offering advanced mathematical manipulation tools with a powerful and intuitive scripting language. Coupled with Simulink, a graphical modular simulation environment, it provides an easy to use modelling and simulation tool. Many industrial companies and universities use MATLAB/Simulink as a standard commercial system simulator for simulation of technical systems. Other, similar, software packages are available, including VisSim (<http://www.vissim.com>), Dymola/Modelica (<http://www.dynasim.se>), Simplorer (<http://www.ansoft.com/>), and the free, open source Scilab/Scicos (<http://www.scicos.org/>),

MATLAB provides multiple toolboxes for optimisation and systems analysis in addition to data acquisition hardware that can be linked to the simulation. While the routines are powerful and varied, development of hybrid system simulations is not trivial. The Simulink interface is easy-to-use, but the platform assumes that the system is readily modelled as a system of differential equations. The solvers can be sensitive with closed-loop, non-linear systems, including hybrid power systems with battery storage. Experience and knowledge of the system behaviour is essential to ensure stable and universal models of different components of PV hybrid systems.

For MATLAB no commercial toolboxes for PV components and systems are available, but several research institutes [8], [9] have created their own toolboxes, see Table 1. . The system simulator Simplorer (www.ansoft.com) has commercially available toolboxes for PV and renewable energy components and systems.

7. Conclusion and recommendations

7.1. Limitations of current tools

Current software tools can greatly simplify and shorten the design process for PV hybrid systems. However they do have limitations. In order to maintain ease of use and limit complexity, dimensioning tools like RETScreen or PV*SOL usually limit the available options for energy sources, system architectures, and dispatch strategies. With simulation tools like HOMER or Hybrid2, very detailed analyses are possible. Both allow the inclusion of wind turbines in the system analysis. Only HOMER and the newest version of PV*SOL (Version 5) which will be available at the end of 2010 allow comparison between DC and AC coupled systems.

The research tools, like TRNSYS and INSEL, and the standard commercial system simulators, like MATLAB, allow much more flexibility in defining energy sources, system architectures, and dispatch strategies, but at the expense of considerably more effort to learn the software and develop the models. For the standard commercial system simulators, with the exception of Simplorer, the models for PV and renewable energy components must be developed by the user, or obtained through cooperation with research institutions that have developed proprietary models. (see Table 1).

A final limitation is that no direct data exchange is possible among the programs. This must be done by using (or developing) an auxiliary program or with paper, pencil and manual input.

7.2. Recommendations for further development

The following improvements are suggested, especially for the dimensioning and simulation tools:

- Incorporate other energy sources, such as wind or hydro turbines, into the hybrid system analysis
- Incorporate the ability to model and compare both DC and AC coupled system architectures

- Provide simpler means for data exchange between different tools. For example, provide the means to export and import to/from a common <neutral> file format.
- Make more use of the open-source approach to software development. Making proprietary models and tools more open would allow further development by a broader community and reduce the risk that valuable work is lost because the original developers no longer have the time or resources to continue maintenance and further development.
- Develop an <intermediate> tool for experienced designers that is more flexible than the basic dimensioning tools but is oriented towards system design rather than to research and simulation. The tool should incorporate the improvements listed above.

7.3. Recommendations for users

The overview in Table 2 and the program descriptions in Section 4 show that each of the programs has its pros and cons. The user must therefore decide which features are most important for his particular needs, and should then test the programs which meet these criteria. Most of the commercial programs are available in time limited demo versions and thus evaluation is possible without a large financial commitment,

One of the key decisions to be made by the user concerns the desired focus of the calculations: preliminary feasibility study and general dimensioning (RETScreen), economic considerations (HOMER), a detailed technical configuration (PV-SPS, PV*SOL, PVsyst), system analysis (Hybrid2, PV-DesignPro) or detailed research (TRNSYS, MATLAB/Simulink).

In conclusion, it must be pointed out that the results of the system design and system simulation are dependent not only on the calculation algorithms of the program concerned, but also to a large extent on the quality of the input data. The quality of the input data depends very much on the technical knowledge and experience of the program user.

These software tools can prove a very useful aid during the process of system design and analysis. The output results, however, should always be appraised with due

critical objectivity! All participants of the Task 11 survey reported that they use basic paper and pencil calculations, and sometimes simple spreadsheet programs, to obtain a first estimate of system output and behaviour before applying the software tools so that they have an independent check on the results.

8. Literature

[1] Anja Lippkau, Analyse von Dimensionierungs- und Simulations- Software für Hybrid-Insel- Systeme mit PV-Generator, Diesel-Generator und Batterie, Diploma thesis at SunTechnics Hamburg and FHTW Berlin (University of Applied Sciences), Germany, 2006

[2] Anja Lippkau, Timon Kampschulte, Simulation of hybrid systems, Sun & Wind Energy 2/2007, Germany

[3] Dave Turcotte, Michael Ross, Farah Sheriff, Photovoltaic hybrid system sizing and simulation tools: Status and Needs, PV Horizon: Workshop on Photovoltaic hybrid systems, Montreal, Canada, 2001

[4] Presentations at the workshop on “Software tools for PV hybrid design and simulation”, in Valencia, Spain, 2008, www.iea-pvps-task11.org

[5] Geoffrey T. Klise, Joshua S. Stein,” Models Used to Assess the Performance of Photovoltaic Systems”, Sandia National Laboratories Report SAND2009-8258, Albuquerque NM, USA, 2009

[6] Ortmeyer, T., R. Dugan, D. Crudele, T. Key, and P. Barker, “*Renewable Systems Interconnection Study: Utility Models, Analysis, and Simulation Tools*”, Report SAND2008-0945P, Sandia National Laboratories, Albuquerque, NM, 2008.

[7] David L. King, William E. Boyson, Jay A. Kratochvil, “Photovoltaic Array Performance Model”, Sandia National Laboratories Report SAND2004-3535, Albuquerque NM, USA, 2004

[8] A. D. Hansen, P. Soerensen, L. H. Hansen, H. Bindner, “Models for a Stand-Alone PV System”, Risoe report R-1219(EN)/SEC-R-12, ISBN 87-550-2774-1, Roskilde, Denmark, 2000, <http://www.solenergi.dk/rapporter/pdf/sec-r-12.pdf>

[9] Francisco M. González-Longatt, “Model of Photovoltaic Module in MATLAB™”, 2do CONGRESO IBEROAMERICANO DE ESTUDIANTES DE INGENIERÍA ELÉCTRICA, ELECTRÓNICA Y COMPUTACIÓN “CIBELEC”, Puerto la Cruz, Venezuela, 2006, <http://sites.univ-reunion.fr/masterCE/Heuristique/ModelPV.pdf>