Collaborative Project

CLIM-RUN

Climate Local Information in the Mediterranean region Responding to User Needs

WP 7: Renewable Energy

MONTH 12

D 7.3: Climate Information and Renewable Energy

Simplified Energy Models

MS32, MS34

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1. Introduction

Energy models are simplified representations of real energy systems. Models are convenient tools in situations where performing tests or experiments in real world are impractical or impossible.

Some advantages of using computer models in general include:
–They are explicit; their assumptions are documented
–They compute the logical consequences of the modeller's assumptions
–Comprehensive and able to interrelate many factors simultaneously

Energy models are useful as they depict immensely complicated systems. For solar and wind energy technology applications, temporal mismatching of energy resources with the energy demand is a common phenomena. This mismatching has a major influence in designing solar or wind energy system components. Thus individual components are carefully modelled in acceptable accuracy in order to predict the final energy yield.

There is a wide spectrum of Solar and Wind energy models. For the purpose of CLIMRUN project, we will be interested in the logistical (e.g. time series / probabilistic) models. RETSCREEN, PVSYST http://www.pvsyst.com/, HOMER https://analysis.nrel.gov/homer/, SAM https://sam.nrel.gov/, WAsP http://www.wasp.dk/etc. are some of the commonly used logistical models. In the renewable energy community there exist several software tools and models. Some are commercial, some are free while some are being developed and used exclusively for limited and restricted usage. Each rely on different modelling approach and no single tool is best for all purposes. Some models have both solar and wind energy as their coverage technology area. SAM, RETSCREEN, INSEL, TRNSYS, HOMER are such models.

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 optimize for different objectives. Some will attempt to explicitly minimize 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.

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.

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 organizations; 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.

2. Solar Energy Models

Many sizing programs create hourly stochastic series of weather data in an attempt to model changeable sunny and cloudy periods. Then they use a model of the solar power plant under different irradiances and temperatures, to try to calculate kWh/kW over a year by summing up the expected energy yield at each hour interval.

2.1 PV plant yield models

There exist a number of models which are being used in the PV industry. A comparative survey of such models was conducted under CLIMRUN project. In the following four tables major findings are tabulated.

Table1: Availability of PV tools (source [1]
(dim: dimensioning tool, des: mini-grid design tool, sim: simulation tool, res: research tool)

free tools

RETScreen	dim
HOMER	sim/dim
Hybrid2	sim
Vipor *	des
Jpélec *	des

* Mini grid design

commercial tools

Off Grid Pro	dim
PVsyst	sim/dim
PV*SOL	sim/dim
Solar Pro	sim

standard commercial system simulators

Simplorer (APL)	
PowerSim	res
MATLAB/Simulink	res
Dymola	res
PowerFactory	res

internal tools

Off Grid Sizer	dim	Conergy
Sunny Island Design	dim	SMA
PVS	sim/dim	ISE
TALCO	res	ISE
Dymola	res	ISE
MATLAB/Simulink PVToolbox	res	Canmet
MATLAB/Simulink Hysis	res	CIEMAT
MATLAB/Simulink N.N.	res	ISET
PowerFactory Tool box	res	ISET

Table 2: Overview of a few programs (source [1])

(+ good/easy, o satisfactory, - sufficent/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 Parts1, 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

Table 3: Overview of a few selected PV models (source[2])

Software	Dimensioning - Software		Dimensioning + Simulation - Software		
Programmme	PV-SPS	RETScreen	PV-SOL	PVSYST	Hybrid2
Version	2.0	version 3.2	2.6 R5	v3.41	1.3c R3
Year of launch of the recent version	2001	2005	2006	2006	2004
Year of launch of the first version	2001	1997	1998	1994	1998
Costs (single licence)	99 (A $) = 58 Euro	free of charge	498 Euro	700 (CHF) = 465 Euro	free of charge
Language versions	English	English, French	English, French, Spanish, German, Italian	English, French	English
Instruction manual quality	[1]	+	+	detailed F1 assistance	–
User-friendliness	o	+	o	o	–
Component dimensioning [2]	PV-D-B	PV-D-B	PV-B	PV-B	no dimensioning
Simulation [2]	no simulation	no simulation	PV-D-B	PV-D-B	PV-D-B-W
Plausibility check	yes	no	yes	yes	no
Irradiation database	4 locations	yes + NASA link + S	yes + S	yes + S	yes
Emission balance	no	yes	yes	no	yes
Economic analysis	no	yes	yes	yes	yes
Clearness of data input for users	o	+	–	o	–
Clearness of data input for system components	+ [4]	+ [5]	+	o	–
Result output clarity	+	+	o	o	–
Time resolution of the results / hour, day, week, month, year	month, year	month, year	hour, day, week, month, year	hour, day, month, year	user-defined
Project report / print-out	o	+	+	+	–
Website	*www.bcse.org.au/ default.asp?id=167*	*www.retscreen. net/ang/t.php*	*www.valentin.de*	*www.pvsyst.com*	*www.ceere.org/rerl/projects/ software/hybrid2*

[1] No separate manual, as 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; (+) = 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.

Table 3: (continuation from last page)

Software Program	Basics				
	Developer	Cost	Web-Based or Application	Weather Data Source	Irradiance Model
HOMER	HOMER ENERGY, originally developed by NREL	free	application	user provides hourly average global solar radiation on the horizontal surface (kW/m^2), monthly average global solar radiation on the horizontal surface ($kWh/m^2/day$), or monthly average clearness index	Hay and Davies model
Polysun	Vela Solaris	Light $159 Pro $489	application	Meteotest	unknown
PV Designer	Solmetric	$400/yr	application	various weather sources including TMY2 and TMY3 data; outside the US, the same weather sources as Energy Plus	Perez et al. model
PV-DesignPro	Maui Solar Energy Software with Sandia	$259	application	TMY2, TMY3 , Meteonorm, Global Solar Irradiation Database	Perez et al. model (default), HDKR model (option)
PV F-Chart	F-Chart Software with University of Wisconsin	$400	application	TMY2, TMY3, weather data can be added	Isotropic Sky model
PV*SOL	Valentin Software	$698 [2]	application	MeteoSyn, Meteonorm, SWERA, PVGIS, NASA SSE	Hay and Davies model
PVsyst	University of Geneva	1st license $984, additional $197	application	TMY2, TMY3, Meteonorm, ISM-EMPA, Helioclim-1 and -3, NASA-SSE, WRDC, PVGIS-ESRA and RETScreen; user can import custom data in a CSV file	Hay and Davies model (default), Perez et al. model (option)
PVWatts v. 1	NREL	free	Web	in the US—TMY2 data; 239 options outside the US—TMY data from the Solar and Wind Energy Resource Assessment Programme, the International Weather for Energy Calculations (V1.1), and the Canadian Weather for Energy Calculations	Perez et al. model
PVWatts v. 2	NREL	free	Web	combination of TMY2 data with monthly weather data from Real-Time Nephanalysis (RTNEPH) database (cloud cover), Canadian Center for Remote Sensing (albedo), National Climatic Data Center (daily maximum dry bulb temperatures) and RDI/FT Energy (1999 residential electric rates)	Perez et al. model
RetScreen	Natural Resources Canada	free	application	combination of weather data collected from 4,720 sites from 20 different sources with data from 1961–1990 & NASA-SSE	Isotropic Sky model
Solar Advisor Model (SAM)	NREL	free	application	TMY2, TMY3, EPW, Meteronorm	Perez et al. model (default); Isotropic Sky Model, Hay and Davies model, Reindl model (options); total and beam (default), beam and diffuse (option)

Notes:

[1] Some entries in this table adopted from Klise and Stein (2009). [2] Does not include expert version to be released in 2010.

[3] Shading derate is from SunEye readings. Inverter efficiency derate is from an equipment database.

[4] User enters array operating temperature, reference efficiency, temperature coefficient and array area.

Table 3: (continuation from last page)

Modeling					
Production-Estimating Model: Module	Production-Estimating Model: Inverter	Simulation Frequency	Tilt	Orientation	Derate Factors
linear irradiance model with temperature correction	single efficiency derate factor	hourly	manual input	manual input	derate factors not categorized, all losses except for single percentage for inverter efficiency are covered by "miscellaneous losses"
empirical model of module performance, dependent on three MPPT power ratings at different irradiance values and the module temperature coefficient	unknown	hourly	manual input	manual input	soiling, degradation, mismatch, wiring
proprietary model based on nominal power and operating temperature	single-weighted efficiency derate factor	hourly	manual input	manual input	PV module nameplate dc rating, inverter and transformer, mismatch, diodes and connections, dc wiring, ac wiring, soiling, system availability, shading, sun tracking, age[3]
Sandia model	Sandia model	hourly	manual input	manual input	wiring, MPPT efficiency, array current derate factor, array voltage derate factor
function of efficiency and temperature	power tracking and power conversion efficiency factors	hourly	manual input	manual input	inverter conversion efficiency and power tracking efficiency
modeled using V and irradiance at STC, module efficiency curve and an incident angle modifier; linear or dynamic temperature model options	inverter profile and efficiency curve generated from measured data	hourly	manual input	manual input	mismatch, diodes, module quality, soiling, wiring, deviation from standard spectrum, module height above ground
Shockley's one-diode model for crystalline silicon; modified one-diode model for thin film	inverter profile and efficiency curve generated from measured data	hourly	manual input	manual input	field thermal loss, standard NOCT factor, Ohmic losses, module quality, mismatch, soiling (annual or monthly), IAM losses
simplified PVFORM	single efficiency derate factor	hourly	manual input	manual input	PV module nameplate dc rating, inverter and transformer, mismatch, diodes and connections, dc wiring, ac wiring, soiling, system availability, shading, sun tracking, age
simplified PVFORM	single efficiency derate factor	monthly	manual input	manual input	PV module nameplate dc rating, inverter and transformer, mismatch, diodes and connections, dc wiring, ac wiring, soiling, system availability, shading, sun tracking, age
Evan's average efficiency model	single efficiency derate factor	monthly	manual input	manual input	inverter efficiency, miscellaneous losses
Sandia model, CEC model, PVWatts model	single efficiency derate factor, Sandia Model for grid-connected inverters	hourly	manual input	manual input	mismatch, diodes and connections, dc wiring, soiling, sun tracking, ac wiring, transformer

Table 3: (continuation from last page)

Software Program	Modeling			Output Data
	Technologies	Tracking	Shading	
HOMER	not technology specific[4]	single axis (horizontal, daily adjustment), single axis (horizontal, weekly adjustment), single axis (horizontal monthly adjustment), single axis (horizontal, continuous adjustment), single axis (vertical, continuous adjustment), dual axis	not considered independently, could be incorporated into single derate factor	hourly ac production data
Polysun	cSi, aSi, CdTe, CIS, CIGS, HIT, µc-Si, Ribbon (EFG)	single axis, dual axis	horizon profile may be defined or imported	unknown
PV Designer	cSi, aSi, CdTe, CIS	n/a	sub-module level shading, computed based on distance-weighted interpolation of readings taken from Solmetric SunEye	hourly ac energy production; daily and monthly ac energy production displayed graphically on screen
PV-DesignPro	cSi, aSi, CdTe, CIS, CPV, mj-CPV	single axis (horizontal axis EW), single axis (horizontal axis NS), single axis (vertical axis), single axis (NS axis parallel to Earth's axis), dual axis	horizon profile user-defined	hourly data available for meteorological data, PV array behavior (cell temp, module efficiency), energy production and more
PV F-Chart	not technology specific [4]	flat-plate array, single-axis tracking (adjustable tilt/ azimuth), dual-axis tracking, concentrating parabolic collector	not considered, could be incorporated into other derate factors	monthly average hourly values of ac energy
PV*SOL	cSi, aSi, CdTe, CIS, HIT, µc-Si, Ribbon	single axis (vertical), dual axis	horizon profile user-defined or imported from shade survey tool, 3D modeling environment in Expert version	hourly energy production in one-week segments
PVsyst	cSi, HIT, CdTe, aSi, CIS, µc-Si	single axis (horizontal axis EW), single axis (vertical axis), single axis (tilted axis), dual axis, dual axis (frame NS), dual axis (frame EW), tracking sun shields; ability to define parameters such as collector width, shade spacing and rotation limits	horizon profile can be user-defined or imported from a shade survey tool, 3D modeling environment, based on array configuration	hourly data available for meteorological data, PV array behavior (cell temp, wiring losses, etc.), energy production
PVWatts v. 1	cSi	single axis, dual axis	single derate factor	hourly ac energy production
PVWatts v. 2	cSi	single axis, dual axis	single derate factor	n/a
RetScreen	cSi, aSi, CdTe, CIS, spherical-Si	single axis, dual axis, azimuth	n/a	n/a
Solar Advisor Model (SAM)	cSi, aSi, CdTe, CIS, CPV, HIT	single axis (tilted NS axis), dual axis	12-month by 24-hour shade profile can be imported	hourly data available for meteorological data, PV array behavior (cell temp, wiring losses, etc.), energy production

Notes:

[4] User enters array operating temperature, reference efficiency, temperature coefficient and array area. n/a = not available

Table 4: Yield modelling tools in 2010 (source [3])

Details			Component Database			
Financial Analyses	**Ability to Export Data to Excel**	**Optimization**	**Module**	**Inverter**	**Update Method and Frequency**	**User Support & Documentation**
cash-flow analysis considering energy costs, operating costs and calculation of LCOE	exported as a text file	sensitivity analysis and optimization capability	n/a	n/a	n/a	user manual provided with software
financial analysis including O&M costs, incentives, projected electricity costs, inflation and interest rates	yes	n/a	yes	yes	automatically checks for updates	user manual provided with software
n/a	yes	n/a	yes	yes	component data complied from PVXchange database, updated approximately monthly	user manual provided with software
basic cash-flow analysis	yes	parametric analysis	yes	yes	updates supplied periodically on the Maui Solar Software site; you can add modules and inverters	online help file, training videos
lifecycle cost calculations including electricity purchased from utility, electricity sold to utility, O&M costs, rebates, tax credits, depreciation; cash-flow analysis	can be copied and pasted into Excel	parametric analysis	n/a	n/a	n/a	user manual provided with software
economic efficiency and cash-flow analysis	yes	tilt, inter-row spacing, inverter loading	yes	yes	updates to the database are supplied by manufacturers; the program can be set to check for updates at start up	limited help file available with program; training available
considers energy costs, feed-in tariffs and system financing	yes	tilt, orientation, inter-row spacing, inverter loading	yes	yes	updated approximately once a year, usually with the release of a software update; you can define additional components or import individual component files received from other sources	detailed help file available with program, FAQ on Web site, no user manual
basic calculation of energy value	8,760 report is output as text that can be pasted into an Excel file	n/a	n/a	n/a	n/a	online documentation and support available
basic calculation of energy value	n/a	n/a	n/a	n/a	n/a	limited help file provided available with program, additional online documen-tation and support available
detailed cash-flow analysis, sensitivity and risk analysis	program is Excel based	n/a	yes	n/a	manufacturer must contact RetScreen	online manual, detailed help file, online training courses
detailed cash-flow analysis for residential, commercial and utility scale projects; focused on the US market; sensitivity and statistical analysis tools	yes	numerous production and financial optimization tools, parametric analysis	yes	yes	CEC module model (NREL maintains a library of CEC-approved modules), SAM can sync with the most recent library, additional modules can be added by contacting NREL; library of inverter coefficients is updated regularly as the CEC inverter database is updated	extensive user manual, detailed help file, online user group, email support

It should be noted that many of these software are being upgraded on a regular basis. Therefore their features are also subject to improvements. For example the software HOMER now has features enabling temporal resolution in minutes interval which is a major development compared to the hourly time step as was originally. There are a few tools like TRNSYS or INSEL where the features are not limited to PV only and offer more flexibility to program and model a specific energy system. They also allow great flexibility in the time steps of the input time series.

TRNSYS :

The weather files distributed with TRNSYS 16 are organised in directories according to the data sources. Currently there are two data sources:

1 The US-TMY2 data sets from NREL (redistributed with NREL's permission). The dataset includes 237 locations in the US (contiguous states + Alaska and Hawaii), and 2 files for Puerto-Rico and Guam.
2 Selected worldwide stations from Meteonorm (distributed under license from Meteotest). More than 1000 locations are included, in more than 150 countries.
3 TRNSYS can perform simulations in flexible time steps. TRNSYS includes PV and Wind energy technology. The user can change the time step for the needs of their simulation. The radiation processing components interpolate and process the data accordingly.

"We typically use a time step of 1 to 5 minutes in our simulations with systems and controllers" -
Matt Duffy
Technical Support Team
Thermal Energy System Specialists, LLC
22 N Carrol St, Suite 300
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2.2 Concentrated solar energy models

Most of the CSP and CPV energy yield models are developed under research initiatives and being used under restricted circulation. Organizations like Sandia Laboratory, NREL, DLR have their own programmes used for specific R&D applications. Unlike PV models CSP and CPV models are yet to reach a matured stage suitable for energy community in general. SAM is perhaps the only model in the year 2011 which has the most of the features of a general purpose Concentrated solar energy system. Therefore the following section is prepared from the user manual of SAM.

SAM:

Table 5: SAM hourly data used

Data Element Name	Description	Units
GHI (W/m^2)	Global horizontal irradiance: Total amount of direct and diffuse solar radiation received on a horizontal surface for the hour.	Wh/m^2
DNI (W/m^2)	Direct normal irradiance: Amount of solar radiation received in one hour within a limited field of view centered on the sun.	Wh/m^2
DHI (W/m^2)	Diffuse horizontal irradiance: Amount of solar radiation received in one hour from the sky, excluding the solar disk on a horizontal surface.	Wh/m^2
Dry-bulb (C)	Average dry bulb temperature for the hour.	°C
Dew-point (C)	Average dew point temperature for the hour.	°C
RHum (%)	Average relative humidity for the hour.	%
Pressure (mbar)	Station pressure or measured atmospheric pressure corrected for temperature and humidity for the hour.	mbar
Wspd (m/s)	Average speed of the wind for the hour.	m/s
Albedo	Ratio of reflected solar radiation to global horizontal radiation. Use -99 for null.	–

The Climate page allows one to choose a weather file in TMY3, TMY2 or EPW format, download satellite derived weather data from the Internet, create user's own weather file in TMY3 format, and review user's weather data. The Climate page displays a summary of the weather data, and also allows to view the actual data in the time series data viewer (DView). The weather files are text files, so one can also examine the data using a text editor, a spreadsheet program, or other software.

Weather Data Guidelines in SAM user manual

For U.S. locations, use the **Best weather data for the U.S.** web link on the Climate page to download a TMY3 file. If the TMY3 database does not include a file for a location at or very near your project site, try to find TMY3 files for locations near the site. You can run simulations for the different locations and compare them to get a sense of what the resource might be at the project site.

SAM comes with the complete set of the 239 TMY2 weather files. To use a TMY2 file, simply choose it from the **Location** list.

If no TMY3 or TMY2 data is available for your project site, you can download typical year data from NREL's Solar Prospector website using SAM's Location Lookup feature. The Solar Prospector website provides access to satellite-derived weather data for the entire U.S. at a 10-km geographic resolution in files using the TMY2 format.

For locations outside of the U.S., EPW files are available for over 1000 locations in 100 countries. If you have weather data from a resource measurement program or from meteorological weather station, you can use SAM's TMY3 creator to create a TMY3 formatted file with the data.

File Formats

A SAM weather file is a file that contains hourly data describing the solar resource, wind speed, temperature, and other weather characteristics at a particular location in one of three text formats: TMY3 comma-delimited text file format (.csv), http://rredc.nrel.gov/solar/old_data/nsrdb/1991-2005/TMY3/TMY2 non-delimited text file format (.tm2), http://rredc.nrel.gov/solar/old_data/nsrdb/tmy2/ EPW comma-delimited text file format (.epw), http://www.eere.energy.gov/buildings/energyplus/weatherdata_format_def.html

The National Renewable Energy Laboratory's typical year data represents average weather data over a range of years: 1961-1990 for TMY2 data, and 1991-2005 for TMY3 data. Each typical year file may contain data from different years within the range, for example a TMY3 file might contain 1995 data for the month of February, 2001 data for March, 1998 data for April, etc. The NREL typical year data is based on analysis of weather data measured at each location and is appropriate for economic and performance predictions of a project over a long analysis period. The EPW data was developed for the U.S. Department of Energy's EnergyPlus building simulation model, and is a source of non-U.S. weather data for SAM. The EPW data on the EnergyPlus website is also typical year data.

TMY3 files are available for 1020 U.S. locations, and are based on more recent data and better modeling techniques than the TMY2 data. However, the TMY3 data was developed using data from a shorter time period than the TMY2 data, so may be less representative of the resource over the long term. (Although the TMY2 data includes effects from the Mt Pinatubo volcanic eruption, which may distort solar energy output predictions based on the data.) If both TMY2 and TMY3 files are available for your project site, you may want to run SAM with both sets of data to compare results.

SAM will read a weather file containing data from any source, as long as it is correctly formatted. You can create your own weather file with data collected from a resource measurement program, or from meteorological stations. SAM may not be able to read weather files that contain formatting errors or erroneous data elements. In some cases, you can use a text editor to compare a problematic file with one in the same format that works correctly in SAM to find problems with the file. Refer to the documentation available in the websites listed above for each file format for details.

Single Year Weather Data

Single year data represents the weather at a location for a specific year. Single year data is appropriate for analysis of a project's economics and performance in a particular year, and for analyses involving time dependent electricity pricing or electric loads for a given year. Single-year weather data can be developed from on-site measurements or from satellite-derived measurements. Single-year data for U.S. locations is available from NREL's Solar Prospector website, follow the link on the Climate page under **Web Links**. The Solar Prospector data is satellite-derived data formatted using the TMY2 file format, so SAM can read the data directly. NREL also publishes the specific-year data used to develop the TMY2 and TMY3 data sets on the websites listed above, but that data must be formatted to work with SAM, either using external software or SAM's TMY3 Creator feature.

Time Convention

The time convention of the weather data determines the time convention of SAM's simulations. For example, TMY2 and TMY3 data both use local standard time, and the radiation data values represent the total energy received during the 60 minutes preceding the indicated hour. The global horizontal radiation shown for hour 1 represents the total radiation incident on a horizontal surface between midnight and 1:00am of the first hour of the year. Both data sets assume that there are 8,760 hours in one year and do not account for leap years. SAM assumes that the solar angle at the middle of the hour (at 30 minutes past the hour) applies to the entire hour.

Weather Data Elements

SAM uses the following data from the weather file:
Atmospheric pressure: CSP, wind
Dew point temperature: CSP
Diffuse horizontal radiation: PV
Direct normal radiation: PV, CSP
Dry bulb temperature: All technologies
Global horizontal radiation: PV, CSP
Hour of the day: All technologies
Latitude: All technologies
Longitude: All technologies
Percent relative humidity: CSP, wind
Site elevation: All technologies
Wet bulb temperature: CSP
Wind direction: Wind
Wind velocity: All technologies

Weather Data Information (Annual)

SAM calculates and displays the annual totals and averages of four of the hourly data columns from the weather file in the weather data information variables. Weather data information variables cannot be edited.

Direct Normal (kWh/m^2)

The sum of the 8,760 hourly values of the direct normal radiation data in the weather file, expressed in kWh per square meter. Direct normal radiation is solar energy that reaches the ground in a straight line from the sun.

To convert this number to kWh per square meter per day, divide it by 365 days/yr.

Global Horizontal (kWh/m^2)

The sum of the 8,760 hourly values of the global horizontal radiation data in the weather file, expressed in kWh per square meter. The global horizontal radiation is the total amount of direct and diffuse solar radiation incident on a horizontal surface over the period of one year.
To convert this number to kWh per square meter per day, divide it by 365 days/yr.

Dry-bulb Temp (°C)
The annual average of the ambient temperature data in the weather file in degrees Celsius.

Wind Speed (m/s)
The annual average wind speed in meters per second.
For NREL TMY2 and TMY3 data, and EPW from the EnergyPlus website, wind speed data is at 10 meters above the ground.

3. Wind Energy Models

3.1. Introduction

Wind turbines harness kinetic energy possessed by moving air. The wind power available per unit area of flow is proportional to the air density and cube of the wind speed. This means for a given percentage change in wind speed, there will be a proportionately greater impact on the power yield of a wind machine. Baker et al.[4] report that a 10% change in wind speed could alter energy yields by 13 to 25%, depending on the site and season.

An excellent overview of the eight different ways the wind resource at a site can be estimated is given in Landberg et. al.[5]. In practice establishment of wind resource measurement infrastructure in an appropriately dense network and record the measurements for a long, say, 10 years is not possible for evaluating the wind resource. Thus the other methods are important. In the present document some of such methods are indicated from the original paper of Landberg et al.
Landberg et al. has defined the regional wind climate. The regional wind climate is calculated from measurements by removing the local effects. Local effects are all effects specific only to the site, namely, shelter from near- by obstacles; effects of roughness and changes in roughness; effects of orography on scales less than 10 km and thermally driven flow. It should be noted that small features in the landscape (like hills, valleys, forests, lakes etc) do not affect the regional wind climate. The following table is made from Landberg et al.

Table 6: Definition of regional wind climate

Term	Definition	Comments
Atlas	Collection of regional wind climates for a large area	Scope: 100-10000 km Scale: O(50 km)
Regional climate	Wind statistics, temporal and spatial variation. Reduced to standard conditions	Scale: O(50 km) Regional validity must be modelled
Resource	The actual long term kinetic energy content of the wind at a specific location and height	Scale: O (1 m)

MCP (Measure-correlate-predict) method is often used at a site where the central idea is that the resource at one site can be determined by using a short time measurement and then correlating these measurements with an overlapping but climatologically representative time series. Climatological representativity is obtained by measuring for long, say, 10 years. Once the resource at the site has been estimated, modeling is required to cary out the micro-siting. This can be done using any of the micro-siting models: WAsP, MS-Micro, Raptor, Raptor-NL. etc.

There are some global databases such as from NCEP/NCAR (National Centers for Environmental Prediction / National Center for Atmospheric Research) and ECMWF (European Centre for Medium-Range Weather Forecasting) who are the result of huge reanalysis effort carried out by the institutions. The databases typically contain wind, temperature and pressure at several heights in a grid covering the entire globe. These databases contain typically 10 years or more of measurements and so the estimates are climatologically stable. Normally geostrophic drag law is applied to extrapolate the wind in the free atmosphere to the surface.

Wind atlas methodology has been applied to a large number of countries including all of EU Europe and countries in Northern Africa. For countries with a tradition of long records and dense networks of observations of the wind, the wind atlas methodology is often preferred. The method directly corrects existing long term measurements for sheltering obstacles, roughness of terrain and orography. The normal way of applying the wind atlas method is by using WAsP. However, any microsacle model can be used, in principle, like MS-Micro, Raptor, Raptor-NL. CFD models can also be used. The wind atlas method has become so popular that it can be called as a de facto standard.

Wind resource of a region can be estimated by atmospheric meso scale models. The grid size of the models is of the order of a few kilometers. A region of a few hundred by few hundred kilometers is typically modeled. This method can be used, in principle, worldwide as global data coverage is available to be applied in this. The common mesoscale models used for wind energy calculations are KAMM, MM5 and MC2.

A slightly different approach is a combination of a mesoscale model (e.g. KAMM) with a microscale model (e.g. WAsP). Instead of trying to resolve all small scale terrain features, the mesoscale modeling stops at a resolution of approximately 5 km. Local predictions are made with a microscale model such as WAsP using output from the mesoscale model as input to the small-scale model. KAMM/WAsP approach as well as WindScape approach (which is a combination of TAPM mesoscale model with Raptor or Rapto-NL microscale model) have been tried before.

3.2. Typical wind energy resource assessment

A typical commercial wind energy project has a wind resource assessment part which lasts at least 15 months to complete, while for a large wind farm it can go up to 3 years. The typical three levels of wind resource assessment as being practised widely are summarized in the table below.

Levels	Source	Tools	Major Issues	Output
1	Publicly available wind data like airports, weather stations, meteorological towers, Reanalysis data (NCAR or ECMWF) Online wind resource mapping applications or non-interactive maps of	RETSCREEN, Spreadsheet based tools	Poor quality for wind projects as shear and turbulence values not available Statistical distribution of	Average annual wind speed; annual average wind direction; average energy density; average approximate annual energy production. Typical energy estimate: +/- 50%

	wind resources like www.3tier.com; www.WindNavigator.com; www.windatlas.dk		wind speed is not available No site specific data Coarse spatial resolution like 5km x 5km grid	
2	From the same source as in level 1 but to include elevation and terrain data for creating a GIS model of the site	WAsP, WindPRO, Windfarmer	Wind data quality is poor; extrapolations are invalid	Average annual wind speed, average annual wind direction, average annual energy density, average annual energy production; Typical energy estimate +/-30%
3	Based on onsite wind measurement and GIS model of site with elevation and terrain data. Source of the wind data is from at least 1 year on site wind monitoring mast data at 3 heights and a different source of long term reference data.	WAsP, WindPRO, Windfarmer	Practically all commercial wind farms depend on level 3 wind resource assessment	Average annual wind speed, direction, energy density; wind shear based on measured wind speed at multiple heights; turbulence; diurnal variation; spatial and temporal extrapolation; capacity factor; wind farm layout and wake losses. Typical energy estimate +/- 10%-15%

3.3. Three most common wind energy models

WAsP (Wind Atlas Analysis and Application Program) is a PC program for predicting wind climates, wind resources, and power productions from wind turbines and wind farms. The predictions are based on wind data measured at stations in the same region. The program includes a complex terrain flow model, a roughness change model, and a model for sheltering obstacles. WAsP is developed and distributed by the Wind Energy Division at Risø DTU, Denmark.
WAsP is used for :

- Wind farm production
- Wind farm efficiency
- Micro-siting of wind turbines

- Power production calculations
- Wind resource mapping
- Wind climate estimation
- Wind atlas generation
- Wind data analysis

When calculating a wind atlas from site data, WAsP does not use the time-series of meteorological data. Instead, WAsP needs a tabular summary of the frequency of occurrence of wind speed versus wind direction. This tabular summary is contained in an observed wind climate file (OWC or *.tab file).

The OWC Wizard is a utility program which produces OWC files from raw wind speed and direction measurements. The time-series of wind speed and direction data are transformed into a table which describes a time-independent summary of the conditions found at the measuring site.
The observed wind climate file contains the frequencies of occurrence of the wind in a number of sectors (the wind rose) and wind speed bins. It further contains the height of observation above ground level and the geographical coordinates (latitude and longitude) of the wind mast.

Data are stored in an ASCII (text) file with the default file name extension 'tab'. The tab-file can be generated by the Observed Wind Climate Wizard or may be prepared from a climatological table using a text editor.

WindPRO is the wind energy software used to model wind farms. Users are able to design wind farms, including wind turbine layout and electrical design. Energy production, turbine noise levels, turbine wake losses, and turbine suitability can be calculated. WindPro uses wind flow modeling inputs from WAsP or CFD software. WindPro is developed by the Danish energy consultant EMD International A/S. WindPRO is trusted by investment banks to create wind energy assessments used to determine financing for proposed wind farms.

WindPRO can optimize a wind farm layout for energy production given turbine spacing, setback distances, noise level and visual constraints. It can also be used to create photomontages in which simulated turbines are overlaid on a photo of a wind farm site, to show what a proposed wind farm would look like if constructed.

WindFarmer is the wind energy software used to calculate turbine wake impacts, energy yield, and site conditions for determining turbine suitability. WindFarmer uses wind modeling inputs from WAsP or CFD software. WindFarmer is developed internally by the independent renewable energy consultant GL Garrad Hassan. WindFarmer can engage several types of wake models, including an Eddy Viscosity wake model which is more complex than the standard PARK model employed by WindPRO, a leading competitor.More recently, the Eddy Viscosity model has been modified to account for previous discrepancies in the wake modelling of large wind farms. **WindFarmer** and WindPRO have both been trusted by investment banks to develop the published wind energy assessments used to determine financing for proposed wind farms.

WindFarmer, like WindPRO, can optimize a wind farm layout for energy yield given turbine spacing, setback distances, shadow flicker, and acoustic noise level constraints. Both products also feature wind farm visualization capabilities.

3.4 Usage of weather data in wind energy models

The following information was obtained by communicating with the respective wind energy model software companies.

WAsP
Time-series of wind data or climatological (statistical) summaries may be obtained from synoptic stations, from stations established for the collection of climatic data or from other sources. In the selection of wind data a number of goals should be aimed at which can be summarized as follows:

- Sufficient time period. At least one year, but preferably several (whole) years.
- Well exposed anemometer, far from buildings and other obstacles. This requirement is often the most difficult to satisfy.
- Accurate description of anemometric conditions and data of 10-min or hourly averages collected for e.g. each 3-hour period throughout the 24-hour day.

Using raw data as the initial data source is generally preferable, since this allows detection of errors in the data which may be undetectable in data summaries. The raw data must be processed by the Climate Analyst or OWC Wizard in order to obtain a statistical summary table that can be employed by WasP.

When calculating a wind atlas from site data, WAsP does not use the time-series of meteorological data. Instead, WAsP needs a tabular summary of the frequency of occurrence of wind speed versus wind direction. This tabular summary is contained in an observed wind climate file (OWC or *.tab file).

The OWC Wizard is a utility program which produces OWC files from raw wind speed and direction measurements. The time-series of wind speed and direction data are transformed into a table which describes a time-independent summary of the conditions found at the measuring site.
The WAsP recommended requirements for the wind measurements are:

- wind data measured at or close to the wind farm site
- mast higher than 2/3 of the hub height; wind data from top anemometer
- anemometer set-up and calibration according to international standards
- temporal resolution: 10 minutes preferred, but 10-min values every hour or three hours are ok too

Time coverage: 20-30 years of data preferred but several (2-3), whole years of data are often used and are ok too. Correlation with long-term measurements strongly recommended in this case. The accuracy and representativity of the WAsP estimate are related to resolution and length of data series; especially the length of the data series (or long-term correlation) is important.

WindPRO
In WindPRO it is recommended to use measurement data from a local mast with measurements as close to hub height as possible. The industry standard is 10 minute measurements covering a

full integers of years. In practice most sites are measured for one full year. WindPRO can deal with any period length but it makes most sense to follow the industry standard. As long as the time series file is an ascii file WindPRO can read it. The METEO object in WindPRO is quite flexible in reading logger files and can read the outcome of most logger software. When the measurements from the logger has been loaded into a METEO object one can post process the data using the WindPRO MCP module.

WINDFARMER

WindFarmer accepts ASCII data directly recorded by mast data loggers. In wind energy applications it is common to measure wind speed at 10-minute intervals. A long dataset is preferred, as this will reduce the historical uncertainty of the wind speed and therefore energy yield prediction. Ideally a 10-year long dataset is preferred. This can also be achieved through MCP methods, which can also be performed in WindFarmer. Note that WindFarmer uses its own algorithms and is independent of WAsP to that extent.

With WindFarmer's MCP+ module one can directly load data recorded at the logger at the site masts as well as data obtained from reference stations, calibrate and clean the data, perform correlations and MCP calculations, derive frequency distributions, wind roses, etc as well as TAB files for inputs to a wind flow modelling software, such as WAsP. Also note that WindFarmer can accept non-integer number of years.

3.5 Two models which are uncommon in the wind energy community

SAM and HOMER can also be used to model energy yield of a small wind system or a wind based hybrid system. SAM also has capability to deal with utility scale wind systems. However, they are not used widely in wind energy community. The following section is made by the user's manual of SAM and HOMER.

i) SAM wind

Small scale wind systems:

“To view the Wind Climate page, click **Wind Climate** in the main window's navigation menu. The Wind Climate page is available for the Small Scale Wind model. Note that the Utility Scale Wind model uses a different set of inputs on the Wind Resource page.

The Wind Resource page allows you to choose a weather file in TMY3, TMY2 or EPW format, download satellite-derived weather data from the Internet, create your own weather file in TMY3 format, and review your weather data”.

Wind Resource Details

The wind resource details group only appears if you have specified Small Scale Wind as the technology in the Technology and Market window. SAM uses these values to estimate the characteristics of the wind at the turbine's hub height.

Shear Coefficient

The power law coefficient characterizes the wind shear, or relationship between height above the ground and wind speed. At most locations, the wind speed increases with height above the ground. The default value of 0.14 is appropriate for flat terrain free of obstructions.

Turbulence Coefficient

The turbulence coefficient characterizes the stability of the air. The default value is 0.1.

Height at which Wind was Measured
The height above the ground in meters of the anemometer used to measure the wind data in the weather file. For the NREL TMY3, TMY2, and the EPW files, the measurement height is 10 meters.

Specifying Wind Resource Parameters
If you are modelling a small scale wind system, you must specify the three parameters describing additional characteristics of the wind resource. SAM uses these parameters to calculate the wind speed at the turbine hub height, assuming that the wind resource data was measured at a different height, typically just 10 meters above the ground.

To specify wind resource parameters:
1. On the Wind Climate page, scroll down to the bottom of the page if the parameters are not visible on your screen.

2. For **Shear Coefficient**, type a value between 0 and 1. The default value of 0.14 is appropriate for turbines on flat land with little vegetation.

3. For **Height at which Wind was Measured**, type the height above the ground at which the wind speeds in the weather file were measured. For the NREL TMY3, TMY2, and the EPW data, the measurement height is 10 meters.

Utility scale wind
The Utility Scale Wind model is for projects involving one or more large-scale turbines with one of the Utility Market financing options.

Wind Resource
The Wind Resource page allows you to download a wind resource data file from the internet by typing location coordinates or an address.
The data is from NREL's Western Wind Dataset, which covers the western United States:
For information about the dataset, see
http://www.nrel.gov/wind/integrationdatasets/western/methodology.

The Utility Scale Wind model uses wind resource data from files in the .swrf format, which is a tab-delimited text format. To see examples of the files, search your computer for "swrf", or look for files with the .swrf extension in the *\exelib\climate_files* folder in your SAM installation folder, which is *\SAM\2011.4.27* by default.

Input Variable Reference

Wind Resource Location

Wind Data File
The name of the file downloaded from the database.

Data Source
The URL pointing to the data used to create the wind data file.

Date Created
The date the wind data was downloaded and the weather file created.

Latitude Requested
The latitude requested in Location Lookup.

Longitude Requested
The longitude requested in Location Lookup.

Latitude
The latitude from the database, which may differ from the requested latitude.

Longitude
The longitude from the database, which may differ from the requested longitude.

Distance from request
The distance between the requested point in Location Lookup and the point in the database.

Elevation
The locations height above sea level.

Click here to view map of (R)equested and (A)ctual locations
Displays a map in your browser showing the location of the requested point from Location Lookup and the actual point in the database.

Location Lookup
Type an address or coordinates for a U.S. location to download specific-year satellite-derived data from the Solar Prospector website. See Using Location Lookup for details.

Add/Remove
Add or remove a folder on your computer from the list of folders SAM searches for files with the TMY2, TMY3, or EPW file extension. SAM will list all weather files in folders that you add to the search list in the location list. See Adding and Removing Weather File Search Paths for details.

Refresh List
Refreshes the list of files in the location list. SAM automatically refreshes the list each time you visit the Wind Climate page. If you add a weather file to one of the folders in the search list, you may need to refresh the list for the file to be visible in the location list.

Copy to project
Embeds the data from a weather file to the project (*.zsam*) file. This useful when you share your project file with another person and do not want to send the weather file separately. Embedding weather data in a project increases the size of the project file. When you copy data to a project, SAM indicates the data with "USER/" in the location list. See Copying Weather Data to a Project for details.

Remove from project
Remove embedded weather data. The button is only active when the active location in the location list is preceded by "USER/."

Annual Average Data
SAM displays annual averages of the wind speed data in the weather file, which contains data for four heights above the ground.

SAM also displays the annual average temperature at 10 meters. The weather file contains temperature data at each wind speed height.

A green check mark indicates the height that SAM will use for simulations, which is based on the turbine's hub height that you specify on the Wind Farm Specifications page.

Wind Resource Details
The wind resource details group only appears if you have specified Small Scale Wind as the technology in the Technology and Market window. SAM uses these values to estimate the characteristics of the wind at the turbine's hub height.

Shear Coefficient
The power law coefficient characterizes the wind shear, or relationship between height above the ground and wind speed. At most locations, the wind speed increases with height above the ground. The default value of 0.14 is appropriate for flat terrain free of obstructions.

Turbulence Coefficient
The turbulence coefficient characterizes the stability of the air. The default value is 0.1.

Height at which Wind was Measured
The height above the ground in meters of the anemometer used to measure the wind data in the weather file. For the NREL TMY3, TMY2, and the EPW files, the measurement height is 10 meters.

ii) HOMER wind

For small wind or Wind based hybrid systems with PV, Diesel or battery bank etc.

Baseline data
The baseline data is the set of 8,760 values representing the average wind speed, expressed in meters per second, for each hour of the year. HOMER displays the monthly averages calculated from the baseline data in the wind resource table and graph.

There are two ways to create baseline data: you can use HOMER to synthesize data, or you can import hourly data from a file.

To synthesize data, you must enter twelve average wind speed values: one for each month of the year. You can also edit the four advanced parameters Enter each month's average wind speed (m/s) in the appropriate row on the stream flow table. As you enter values in the table, HOMER builds a set of 8,760 values, or one wind speed value for each hour of the year. The synthesized data sequence has the specified seasonal and daily patterns, as well as the specified Weibull distribution and autocorrelation. For more information please see the article on synthetic wind data.

To import a file, you must have a text file that contains hourly wind speed data for a single year. Click Import File and open the text file. Although HOMER expects a text file with a '.wnd' extension, you can import a text file with any extension. The first few lines of a properly formatted .wnd file are

shown below. Each of the 8,760 lines in the file should contain a value that represents the average wind speed (in m/s) over a single hour. The first line represents the wind speed between midnight and 1 a.m. on January 1, the second line between 1 a.m. to 2 a.m., and so on.

If you click Enter monthly averages after importing data from a file, HOMER discards the data from the imported file and synthesizes new data based on the twelve monthly average wind speed values and four advanced parameters it calculated from the imported data. You can edit synthesized data by changing values in the monthly wind speed table. To edit values from an imported file, you must edit the file directly and then import the modified file, as described above.

4. Hydro Energy Models

Due to the complexities with modelling hydro energy systems such as:
- Stochastic value of water inflow on a short time range (important for run-through hydro power plants) or medium and long term time range important for both storage and run-through hydro power plants),

- Value of water that is in energy storage (which can be spent immediately or saved for later use when its value might be higher),
- Water inflow that is dependent on more than one meteorological variable (rain and snow, but also warm whether for melting snow and ice),
- Many technical concerns that needs to be taken in account for energy calculation from hydro power plants,
- Decrease in 20-30% of water inflow to hydro power plant might result in much larger energy outputs due to some restrictions such as biological minimum,
- Nature of energy generation from pump hydro power plants which is dependent on the whole energy system,
- Cascade hydro power plants where water output from one hydro power plant can be water inflow for the next one down the waterway; just to name few, hydro energy models are more complex than those for solar and wind energy. Also, description of energy model needs to be more detailed in order to get realistic results.

For the purpose of CLIM-RUN project, and for the purpose of modelling hydro energy in Croatian power system (50% of installed Croatian power capacities are in hydro), model PLEXOS was used for modelling hydro energy.

4.1 Hydro modelling in PLEXOS model

PLEXOS is an electricity simulation model developed by Energy Exemplar (www.energyexemplar.com). PLEXOS has users worldwide and it is used by many of the world largest utilities and system operators. Model uses XML set of rules or Microsoft Access database for encoding documents and data handling. It is based on .NET technology and is run on Windows operating system.

There are four basic simulation engines in PLEXOS: LT Plan (long-term planning module), PASA (for modelling scheduled maintenance and forced outages), MT Schedule (model medium to long term decisions, “decomposes user-definable constraints to shorter term constraints suitable for detailed modelling in ST Schedule) and ST Schedule (short term modelling, can get to five-minute resolution). In that way, each engine gathers results from the previous engine as an input, which

has high value for modelling water value in hydro power plants. Any model input can be stochastic which is important for modelling hydro production curve, water inflow etc.

There are a multitude of ways to model hydro generators and networks of storage in the PLEXOS software. The classes that provide the fundamental building blocks (in order of importance) are:

- Generator
- Storage
- Waterway
- Constraint

4.1.1. Generators

The simplest approach is to define energy constraints to approximate the availability of water (using Generator [Max Energy Day|Week|Month|Year], and [Max Capacity Factor Day|Week|Month|Year]), and a profile of minimum operating levels that represent run-of-river generation (Generator [Min Load]) as in Table 1.

Table 7: Simple energy-constrained hydro during different months in a year (M1 is a January, etc)

Property	Value	Units	Date From	Date To	Pattern
Units	1	-			
Max Capacity	60	MW			
Min Load	5	MW			M1-4,10-12
Min Load	15	MW			M5-9
Max Energy MONTH	15	GWh			M1-4,10-12
Max Energy MONTH	27	GWh			M5-9

Except minimal and maximum load expected from some hydro power plant, Head (starting water inflow) and Tail storage (end storage of water coming out of hydro power plant, important as it might be water inflow for the next hydro power plant in a cascade) can also be defined for more detailed modelling.

Hydro generator efficiency

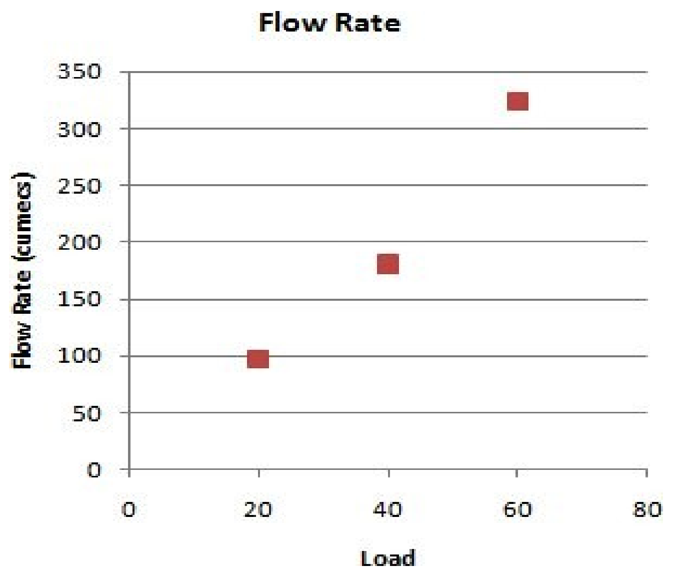
In the Level and Volume models in metric mode, hydro generator efficiency is expressed in megawatts per cubic metre second (MW/cumec) i.e. it is the rate of production that results from a flow rate through the turbine of one cubic meter per second. This efficiency is input via the property Generator [Efficiency Incr].

Hydro generator efficiency is allowed to vary according to the generation level by using [Efficiency Incr] in multiple bands with [Load Point], usually in combination with the “intercept” term [Efficiency Base]. An example is shown in Figure 1 (in metric units).

Table 8: Hydro efficiency curve (metric)

Property	Value	Units	Band
Units	1	-	
Max Capacity	60	MW	
Load Point	20	MW	1
Load Point	40	MW	2
Load Point	60	MW	3
Efficiency Base	58	cumec	
Efficiency Incr	0.5	MW/cumec	1
Efficiency Incr	0.48	MW/cumec	2

Figure 1: Hydro efficiency curve (metric)



4.1.2. Storages

Storages are used to represent storage reservoirs with short, medium, or long-term storage, generator head-ponds and tail-ponds, or even simple junctions in a river-chain. Storage objects are created in the same way as any other object. Each storage can connect to one or more generators or waterways to create a model of a river chain.

There are multiple options for the units of storage, and this is controlled by the Hydro Model database setting.

The Hydro Model selection sets the units used to define hydro storage and hydro generator efficiency. There are three options available:

- Energy (Potential Energy)

- Level
- Volume

Primarily, user needs to choose between a volume-type model (where storage is either in potential energy or volumes of water) and a level-type model where storage is measured in elevation. For these models then storage capacity is defined by either:

- [Max Volume]; or
- [Max Level]

Minimum allowed storage is defined using:

- [Min Volume]; or
- [Min Level]

Initial (period 'zero') storage is defined with:

- [Initial Volume]; or
- [Initial Level]

Storage inflows are defined using the Storage [Natural Inflow] property. Typically this is a dynamic property with values specified hourly or as daily, weekly, or monthly averages.
Constraints can be placed on the amount of release from the storage in any period using the Storage [Min Release] and Storage [Max Release] properties. The rate of change of release can be limited using Storage [Max Ramp].

4.1.3. Waterways

Waterway objects either:

- Connect the storages in their [Storage From] and [Storage To] collections; or
- Spill water from the [Storage From] 'to the sea'.

Combinations of Storage, Waterway, and Generator objects are used to create models of cascading hydro networks with canals and spillways modelled with waterways. Waterway flows can be delayed using the Waterway [Traversal Time] property. Waterways can have bounds placed on their flows using the Waterway [Max Flow] and [Min Flow] properties. The units for these limits, and for reported waterway flows is controlled by the Hydro Model database setting. The rate of change of flow can be controlled using the Waterway [Max Ramp] property.

4.1.4. Constraints

Constraint objects are used to define custom constraints on elements or combination of elements in your hydro system. Constraints can include Generators, Storages, and Waterways in any combination.

4.2. Hydro reservoirs

A cascading hydro network is composed primarily of three distinct storage types:

- Short-term storages;
- Medium-term storage;
- Long-term storages.

Short-term storages like pump storage, regulation tank/canal and small head pond storages can typically regulate water releases within a day and up to a week. Typical medium term storages have the ability to regulate the releasing policy within monthly to yearly periods. Most of these inter-annual storage reservoirs need to be solved in a two step simulation, calling the MT module to solve the high level releasing policy and the detailed generation schedule afterwards.

Long-term storages are those that do not attain their bounds within a one-year period. For these storages the optimization needs to be provided information on the long-term value of the water in storage.

4.2.1. Storage decomposition

The releases from long-term storage reservoirs must be optimized by MT Schedule, which solves over long periods of time (typically one year at a time). When the user also runs ST Schedule, PLEXOS will need to coordinate MT and ST Schedule so that it manages these reservoirs appropriately; thus the process of storage "decomposition". Through settings on MT Schedule, ST Schedule, and the individual Storage objects, user can control many aspects of this decomposition.

4.3. Pumped storage

Pumped storage plants store energy in the form of water, pumped from a lower elevation reservoir (the ‘tail’ storage) to a higher elevation (‘head’ storage). Low-cost off-peak electric power is used to run the pumps. During periods of high electric demand (and high price), the stored water is released through turbines to generate power. Although the losses of the pumping process make these plant a net consumer of energy overall, the system benefits from the arbitrage of cheap off-peak generation into the more expensive on-peak.
PLEXOS does not have a specific ‘type’ setting for pumped storage hydro plant. Instead pumped storage is modelled using the generic Generator class and are identified by their unique data:

- Generator [Pump Load];
- Generator [Pump Efficiency]

Pump Load is the megawatt load drawn from units in pumping mode.

Pump Efficiency is the round-trip percentage efficiency of the pumped storage plant. For example an efficiency of 75% implies that for every unit of generation then 1/0,75 = 1.3333 units of energy are required to pump the required water back to the head storage. Further this implies that the price received when generating must be at least 33.33% higher than the price paid for pump energy.

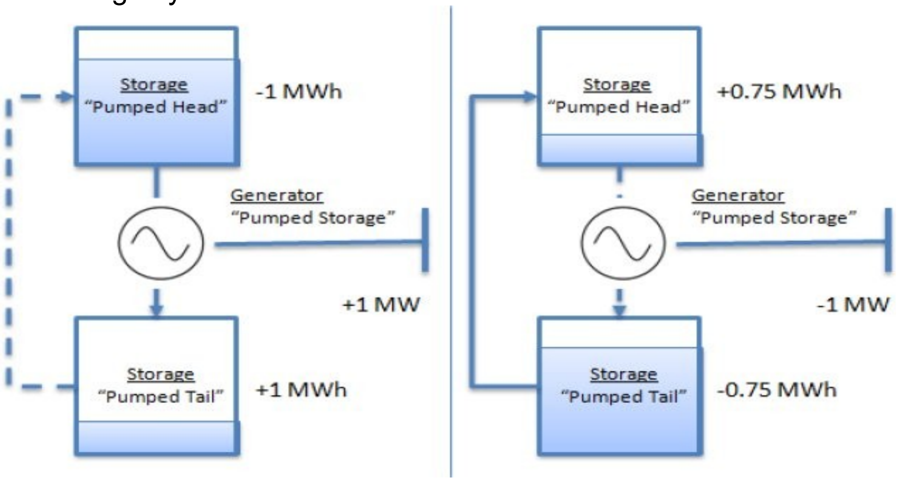
These two properties identify the Generator as a pumped storage, but you must also model the connected storages. Thus two Storage objects are required:

- One for the Generator [Head Storage]; and

- One for the Generator [Tail Storage].

You need only define the Storage [Max Volume] on these storages.

Figure 2: Pumped storage cycle

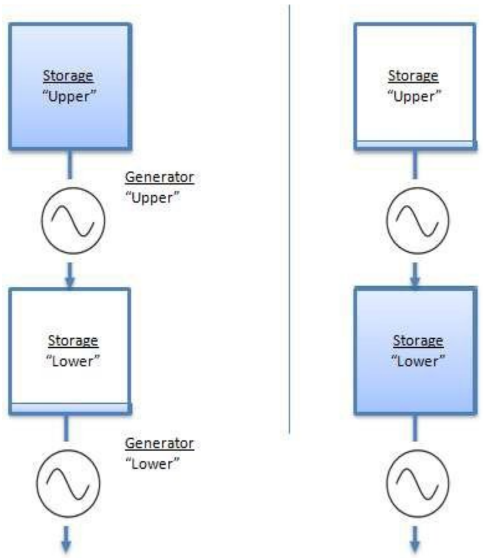


4.4. Cascade hydro systems

4.4.1. The potential energy model

When one considers a cascade of storages with multiple generators, however, the potential energy in the system is not simply a function of the total volume of water in the system, but also of which storages are holding that water. Consider a system with two storages and identical generators in a linear cascade like Figure 3. On the left the upper storage is full, the lower is empty and vice versa on the right. The potential energy in the left-hand system is double that of the right-hand system. This is because water stored in the upper storage can generate in both the upper and lower generators, whereas water in the lower storage can only generate in the lower generator.

Figure 3: Simple cascade



4.5. Plexos units

Table 9: Hydro unit conversions

Unit	Equivalent
1 acre	43,560 square feet
1 feet	0.3048 metres
1 cubic metre	35.3146667 cubic feet
1 acre-feet	1233.489238 cubic metres
1 cubic metre per second (cumecs)	3600 cubic metres per hour
1 acre-feet	0.3426 cumecs
1 cumecs	2.9186 acre-feet
1 cumec day (CMD)	86400 cubic metres
1 CMD	24 cumecs
1 CMD	70.0456 acre-feet

4.6. Input inflow file example

For modelling meteorological values, data files can be used that are attached to each of power plants modelled. Table 4 shows an example of inflow input file for one hydro power plant from Croatian power system described 15th of March, 2010. File is prepared in .csv format.

Table 10: Inflow file

Year	Month	Day	Period	Value
2010	3	15	1	51,711
2010	3	15	2	51,711
2010	3	15	3	51,711
2010	3	15	4	51,711
2010	3	15	5	51,711
2010	3	15	6	51,711
2010	3	15	7	51,711
2010	3	15	8	51,711
2010	3	15	9	51,711
2010	3	15	10	51,711
2010	3	15	11	51,711
2010	3	15	12	51,711
2010	3	15	13	51,711
2010	3	15	14	51,711
2010	3	15	15	51,711
2010	3	15	16	51,711
2010	3	15	17	51,711
2010	3	15	18	51,711
2010	3	15	19	51,711
2010	3	15	20	51,711
2010	3	15	21	51,711
2010	3	15	22	51,711
2010	3	15	23	51,711
2010	3	15	24	52,502

5. References

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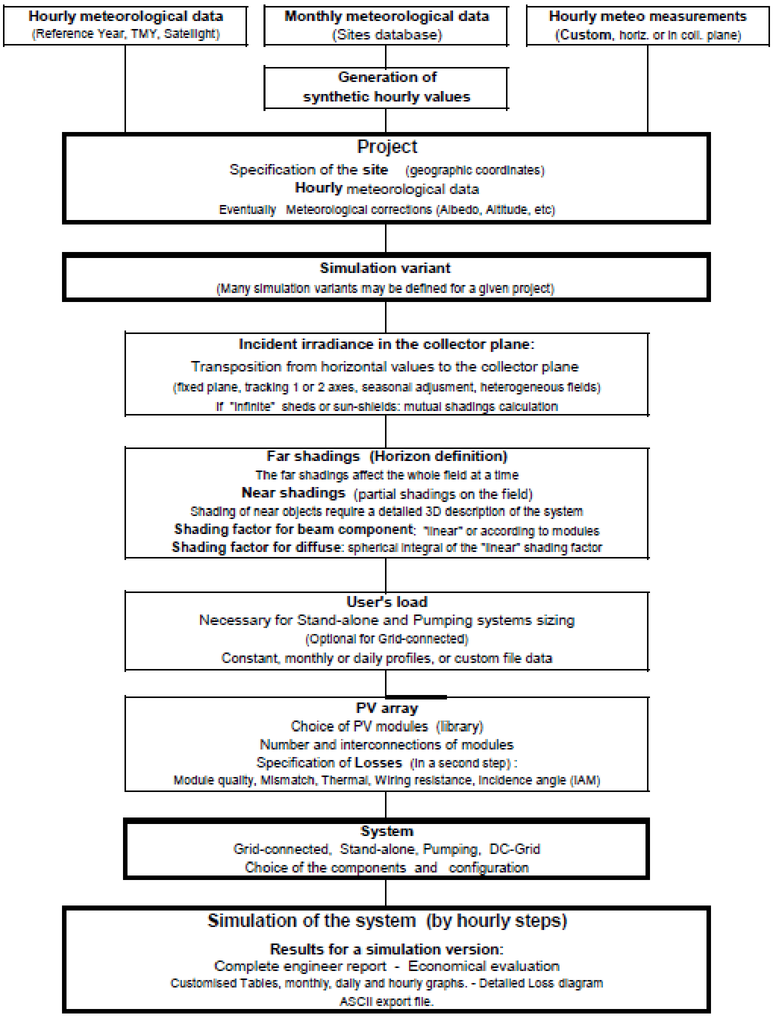
6. Appendix

a) PVSYST basic flow chart



b) Incident irradiation models in PVSYST

Irradiation on the PV-field

We call " **effective incident irradiation**" **Heff** the luminous energy actually falling on the **PV cells**. It is obtained according to the following steps:

- If only monthly meteorological data available: Generation of **hourly synthetic** meteo data (horizontal global irradiance and temperature),
- If diffuse irradiance measured data not available: **diffuse irradiance model** ,
- If **horizon** (far shadings): calculation of the beam effective component (in this version of the program, the diffuse is considered as not affected by horizon).

At this stage, we have the Horizontal **global, diffuse and beam** components at disposal, with the relation: Gh = Dh + Bh.

- Computation of the so-called "**incident energy**" by a **Transposition model** , i.e. calculation of the irradiance on the PV tilted plane.
At this stage, the plane irradiance is composed of **global, diffuse, beam** and **albedo** components, with the relation: Gp = Dp + Bp + Ap.
- Applying the **near shading** calculations (shading factor on beam, diffuse and albedo components), either linear or according to electrical array connexions,
- Applying the **IAM** (Incidence Angle Modifier factor),
this finally results in the **Geff irradiance,** the flux effectively useable for PV conversion. **Heff** will be the corresponding irradiation over a given time period.
Note: we usually use G for designing irradiances (flux expressed in [W/m²]) and H for irradiations (energies in [kWh/m²].

Meteo Monthly calculations
This simplified computation performs **quick meteo evaluations**, using geographical site database only (i.e.monthly irradiation values), and evaluates horizon, tilt, sheds and sun-shields, as well IAM effects.
This method takes advantage of so-called "average months" properties. With real meteo data of a given month, when constructing an "average day" by averaging separately the irradiances at each hour (i.e. all irradiances at 8:00, 9:00, 10:00, etc), we obtain an average profile which is very close to the "Clear day" model profile, with amplitude reduced in such a way that the day integral matches the monthly global value. This also holds for the diffuse component.
Therefore, inversely, for the middle of each month, we construct a "clear day" with amplitude suited to the given monthly irradiation. We then assume that this "average day" is representative of the month, so that we can apply all mentioned corrections (transposition, shadings, etc) using the solar geometry of this middle-month day.

Accuracy
This procedure avoids constructing synthetic hourly values, and gives instantaneous evaluations with very acceptable accuracy.
By respect to an hourly computation, **monthly calculations** for Geneva show that the transposition on tilted plane induces a yearly MBE of the order of:
South plane, tilt 0..90°: < 1.3% SE or SW planes: tilt 45°: < 1.1%, tilt 90° : < 4.1%,
E or W planes: tilt 45°: < 2.7%, tilt 90° : < 11 %, If only the **global** monthly values are known, the uncertainty on the **monthly diffuse** estimation correlation model (about 5%) may induce 1 to 4 % error more.

Transposition model
Transposition is the calculation of the incident irradiance on a **tilted plane**, from the horizontal irradiance data. PVSYST offers two transposition models: - **Hay's model**, a classic and robust model which gives good results even when the knowledge of the diffuse irradiation is not perfect,
- Perez model (Perez, Ineichen et al.), is a more sophisticated model requiring good (well measured) horizontal data.
Transposition is separately calculated for each irradiance component:
- The **beam** component involves a purely geometrical transformation (cosine effect), which does'nt involve any physical assumption.
- The two models differ by the **diffuse** component treatment:
In the **Hay** model, the diffuse irradiance is divided into an *isotropic* contribution, and a *"circumsolar"* proportional to the beam component. Through transposition, the half-sphere isotropic part is reduced according to the vault of heaven's solid angle "seen" by the plane (i.e; the fraction (1+cosi)/2, where i is the tilt angle). The circumsolar is transposed geometrically as the beam

component. The specifity of the Hay model is the determination of the circumsolar fraction, which is chosen as the Clearness index Kb of the beam component.
The **Perez-Ineichen** model introduces the *"horizon band"* as a third diffuse component. It divides the sky into sectors, and parametrises the transformations of the circumsolar and the horizon band according to correlations established on the basis of data of several dozen of measurement sites, distributed all over the world.
- The **albedo** component is evaluated in the same manner in both models, as a given fraction (the "albedo coefficient ") of the global, weighted by the "orange slice" fraction defined between the horizontal and the tilted plane extension (i.e. the half sphere complement of the "seen" vault of heaven), which is the fraction (1- cosi)/2 of the half-sphere.

Validations
During validations of the software, we tested these two models with the data of each site. The comparison of their mean errors (MBE) presents a systematic difference of 1.8 to 2.2% depending on the (Swiss) sites, while the standard deviations RMSE are comparable in all cases. It appears therefore that the Perez's model, which is more complex and especially more sensitive to a realistic determination of the diffuse irradiation, is often not justified in the PVSYST software. Therefore, by default, the PVSYST programme uses the **Hay's model.**
However, if the user can avail of good measurements of the diffuse irradiance, he can choose the most sophisticated model of **Perez-Ineichen** (main menu: option " *Preferences* " / " *Preferences* ").

The Hay transposition model
The Hay transposition model applies differently to the different components of the irradiance.
The **Beam component** results of a pure geometrical transformation:
BeamInc = BeamHor * sin Hsoli / sin Hsol
The Diffuse component is supposed to be mainly constituted of an isotropic distribution, and a circum-solar contribution proportional to Kb DiffInc = DiffHor * [(1-Kb) * (1 + cos i) / 2 + Kb * sin HsolI / sin Hsol]
The **Albedo component** is the irradiance reflected by the ground "seen" by the plane :
AlbInc = * GlobHor * (1 - cos i) / 2 where i = Plane tilt
Hsol = Sun height on horizontal plane
Hsoli = Sun height on the plane (= 90° - incidence angle)
Kb = Clearness index of beam = BeamHor / (Io * Sin Hsol)
Io = Solar constant (depends on the day of year) = **Albedo coefficient** (usual value 0.2)
The expression (1 + cos i) / 2 is the mathematical result of the spherical integral of a constant irradiance, from all directions "seen" by the plane (i.e. the orange slice between the plane and the horizontal).

Diffuse Irradiance model
When it is not explicitly measured, the diffuse irradiation should be estimated from horizontal global by a model. We can mention two wide-used such models:
- **Liu and Jordan's correlation,** which results from an experimental correlation of the D/G ratio by respect to the **clearness index Kt** .
- **Perez model** (Perez, Ineichen et al.), is a more sophisticated model taking hourly data sequence into account.

In PVSYST the diffuse irradiation uses the "robust" **Liu and Jordan's correlation**. When applied to our data from the SIG (the only simultaneous measurement of global and diffuse irradiations we have at our disposal), this correlation gives good results with an MBE of 1.7% and a RMSE of 27% (with respect to the value of the diffuse irradiance), or 13% (referred to global irradiance).

Note: The most sophisticated model of Perez-Ineichen has also been tested, but does not give significantly better results. From the opinion of one of the authors (P. Ineichen in our laboratory, who has also evaluated the Liu-Jordan correlation) this is especially suited for very well-measured data.
Applying it to synthetic hourly data doesn't make great sense.
This is the reason why we didn't implement it in the current version. Nevertheless we intend to offer it as an option it in a further version.

Synthetic data generation
Synthetic data generation provides a mean of constructing meteorological **hourly** data from only **monthly** known values. This is required since numerous simulation processes have to be computed as instantaneous values (or pseudo-instantaneous as hourly averages). This is the case, for example, with the transposition model which closely depends on the solar geometry.

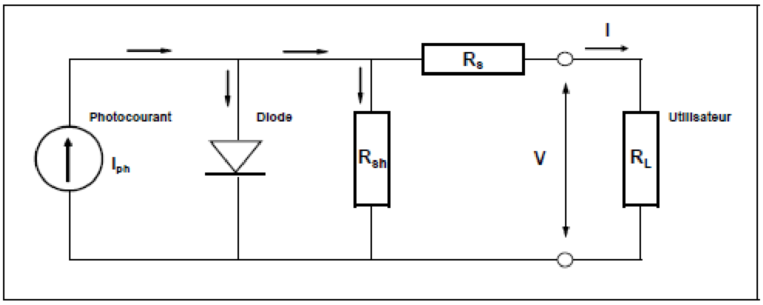
Irradiance generation
For global irradiance, we dispose of well-established random algorithms (Aguiar et al), which produce hourly distributions presenting statistical properties very close to real data.
The algorithm first constructs a random sequence of **daily values**, using a Library of Markov Transition Matrices (probability matrices) constructed from real meteo hourly data of several dozen of stations all over the world. Then it applies a time-dependent, Autoregressive, Gaussian Model for Generating the **hourly sequences** for each day.

Temperature generation
For temperature, such a general model doesn't exist. We used procedures adjusted only on Swiss meteo data (Scartezzini et al.), for which generalisation to any world climate is not proved.
In fact the ambient temperature **daily sequence** shows only weak correlations to global irradiation. Of course the temperature should be continuous, therefore this sequence is constructed using essentially randomly daily *slopes*, with constraints on the monthly average.
But **daily profile** can be much more related to the global irradiance. During the day, temperature behaves rather like a sinusoïd, with amplitude related to the global daily irradiance, and a phase shift of two to three hours. The corresponding correlation parameters (for amplitude and phase shift) have been quantified from several Swiss region typologies. One can accept that these can be generalised to analogous typologies for other places in the world.

Notes: The region typology asked by the program is only used to refine these temperature daily profile parameters. The dependence of PV-system behaviour is not very temperature-sensitive (about 0.4%/°C).

c) Basic energy yield model in PVSYST for crystalline silicon

To describe the operating of a PV module, we use the Shockley's simple "one diode" model (primarily designed for a single cell), described. This model is based on the
following equivalent circuit for describing a PV cvell:



The model was primarily developed for a single cell. Its generalisation to the whole module implies that all cells are considered as rigorously identical.

A more sophisticated model, implying 2 different diodes, is sometimes proposed for the very accurate modelling of a single cell. But in PVsyst, we think that small discrepancies in the cell parameters, inducing internal mismatch, as well as the moderate accuracy of our basic input parameters (usually from manufacturer), make no sense to use it. In the one-diode model the two diodes are considered identical, and the Gamma factor - ranging theoretically from 1 to 2 - defines the mix between them. This model is well-suited for the description of the Si-crystalline modules, but needs some adaptations for reproducing the **thin film technologie module behaviour.** We observed that the CIS technology obeys quite well to this standard model.
The main expression describing the general "one-diode" model is written as:
I = Iph - Io [exp (q · (V+I·Rs) / (Ncs·Gamma·k·Tc)) - 1] - (V + I·Rs) / Rsh
with :

I = Current supplied by the module [A].
V = Voltage at the terminals of the module [V].
Iph = Photocurrent [A], proportional to the irradiance G, with a correction as function of Tc (see below).
ID = Diode current, is the product Io · [exp( ) -1].
Io = inverse saturation current, depending on the temperature [A] (see expression below).
Rs = Series resistance [ohm].
Rsh = Shunt resistance [ohm].
q = Charge of the electron = 1.602·E-19 Coulomb
k = Bolzmann's constant = 1.381 E-23 J/K.
Gamma = Diode quality factor, normally between 1 and 2
Ncs = Number of cells in series.
Tc = Effective temperature of the cells [Kelvin]
The photocurrent varies with **irradiance and temperature**: it will be determined with respect to the values given for reference conditions (Gref, Tref):
Iph = (G / Gref) · [Iph ref + muISC (Tc - Tc ref)]
where G and Gref = effective and reference irradiance [W/m²].
Tc and Tc ref = effective and reference cell's temperature [°K].
muISC = temperature coefficient of the photocurrent (or short-circuit current).
The diode's reverse saturation current is supposed to vary with the **temperature** according to the expression:
Io = Io ref (Tc / Tc ref)3 · exp [(q · EGap / Gamma · k) · (1 / Tc ref - 1 / Tc)]
where EGap = Gap's energy of the material (1.12 eV for cristalline Si, 1.03 eV for CIS, 1.7 eV for amorphous silicon, 1.5 eV for CdTe).

Determination of the model parameters
Thus for a given temperature and irradiance, we have a model based on 5 unknown parameters (**Rsh, Rsh, Iph, Io ref and Gamma,**).
The value of the **shunt resistance Rsh**, representing the inverse of the slope of the plateau I(V) for low V, will be independently treated (that is, fixed in the equations). As it is not possible to deduce it from the manufacturer's datasheet, PVsyst has to choose a **default value** for processing the Database. In order to determine the 4 remaining parameters, we can write the 4 equations below, for the specified reference conditions Gref and Tc ref :

- I(V) at point V=0 (short circuit),
- I(V) at point I=0 (open circuit),
- I(V) at any other point, close to the maximum power point.
  – The derivative muVco = dVco / dTc.

These equations are based on the following parameters (manufacturer's or measured data):
ISCref = Short-circuit current at reference conditions.
Vco ref = Open circuit voltage at reference conditions.
Impref, Vmpref = Current / Voltage at any point (close to the MPP).
muIsc = temperature coefficient of the short-circuit current.
muVco = temperature coefficient of the open circuit voltage.

d) PV model in INSEL

The model of the PV module has two parts: an electrical model (the two diode model") and a thermal model based on an energy balance.

Electrical model The relationship between voltage V_c / V of a crystalline silicon solar cell and current density j / A m^{-2} is given by the two-diode-model equation

$$j = j_{ph} - j_s \left(\exp\left(\frac{q(V_c + j r_s)}{\alpha k T} \right) - 1 \right) - j_r \left(\exp\left(\frac{q(V_c + j r_s)}{\beta k T} \right) - 1 \right) - \frac{V_c + j r_s}{r_{sh}}$$

where

r_s	Series resistance parameter of the cell / Ω m^2
r_{sh}	Shunt resistance parameter / Ω m^2
α	Diode parameter (should be set to 1 in case of the standard two diode model)
β	Diode parameter (should be set to 2 in case of the standard two diode model)
T	Cell temperature / K
q	Charge of an electron (1.6021×10^{-19}As)
k	Boltzmann constant (1.3854×10^{-23}JK^{-1})

Hence, the operating point of the PV generator is given by
V = VcNs

I = jAcNp

where
Ac Area of a single cell / m2
Ns Number of cells in series (whole generator)
Np Number of cells in parallel (whole generator)
The light-generated current density jph / Am2 is proportional to the global radiation G / Wm2 on the generator plane and is assumed to be linearly dependent on the cell temperature T / K
jph = (cph + ctT) G

where
cph Coe_cient of light-generated current density / V1

c_t Temperature coefficient of light-generated current density / $V^{-1} K^{-1}$

The dependence of the saturation current densities j_s and j_r on temperature is given by

$$j_s = c_s T^3 \exp\left(-\frac{qV_{gap}}{kT}\right)$$

$$j_r = c_r T^{5/2} \exp\left(-\frac{qV_{gap}}{2kT}\right)$$

where

c_s Coefficient of saturation current density / $A\,m^{-2} K^{-3}$

c_r Coefficient of saturation current density / $A\,m^{-2} K^{-5/2}$

V_{gap} Band gap (Silicon 1.12 V). The dependence of the band gap on cell temperature is neglected.

Thermal model The thermal model is based on an energy balance

$$m_{mod} N_{mod} c_{mod} \frac{dT}{dt} + P_{el} = \dot{Q}_G - \dot{Q}_r - \dot{Q}_c$$

where

m_{mod} Mass of a PV module / kg

c_{mod} Specific heat of a PV module $J\,kg^{-1} K^{-1}$

P_{el} Electrical power output of the generator / W

$\dot{Q}_G$ Insolation on the whole generator / W

$\dot{Q}_r$ Losses through radiation / W

$\dot{Q}_c$ Losses through convection / W

The absorbed insolation is modeled by

$$\dot{Q}_G = aG(t) A_{mod} N_{mod}$$

The coefficient a of absorption is assumed to be constant. Losses through radiation are modeled by

$$\dot{Q}_r = 2\epsilon A_{mod} N_{mod} \sigma (T^4 - {T_a}^4)$$

where

ϵ Emission factor

σ Stefan-Boltzmann Constant ($5.6697 \times 10^{-8}\mathrm{Wm^{-2}K^{-4}}$)

T_a Ambient temperature / K

Losses through convection are given by

$$\dot{Q}_c = 2\gamma A_{mod} N_{mod} (T - T_a)$$

In case of free convection the heat loss coefficient γ is set to

$$\gamma_f = 1.78\,(T - T_a)^{1/3}$$

forced convection is modeled through

$$\gamma_w = \frac{4.77\, v_w{}^{0.8} (\ell_{mod} N_{mod})^{-0.2}}{1 - 0.17\, v_w{}^{-0.1} (\ell_{mod} N_{mod})^{-0.1}}$$

with wind speed v_w. In case of mixed convection γ is set to

$$\gamma = \sqrt[3]{\gamma_f{}^3 + \gamma_w{}^3}$$

e) Solar radiation calculation in HOMER

In the solar resource input window you specify, for each time step, the *global horizontal radiation*. That is the total amount of solar radiation striking the horizontal surface on the earth. But the power output of the PV array depends on the amount of radiation striking the surface of the PV array, which in general is not horizontal. So in each time step, HOMER must calculate the global solar radiation incident on the surface of the PV array. This article describes that process, which is based on the methods in the first two chapters of Duffie and Beckman (1991)

We can describe the orientation of the PV array using two parameters, a slope and an azimuth. The slope is the angle formed between the surface of the panel and the horizontal, so a slope of zero indicates a horizontal orientation, whereas a 90° slope indicates a vertical orientation. The azimuth is the direction towards which the surface faces. HOMER uses the convention whereby zero azimuth corresponds to due south, and positive values refer to west-facing orientations. So an azimuth of -45° corresponds to a southeast-facing orientation, and an azimuth of 90° corresponds to a west-facing orientation.

The other factors relevant to the geometry of the situation are the latitude, the time of year, and the time of day. The time of year affects the solar declination, which is the latitude at which the sun's rays are perpendicular to the earth's surface at solar noon. HOMER uses the following equation to calculate the solar declination:

$$\delta = 23.45° \sin\left(360° \frac{284 + n}{365}\right)$$

Where: n is the day of the year [a number 1 through 365]

The time of day affects the location of the sun in the sky, which we can describe by an hour angle. HOMER uses the convention whereby the hour angle is zero at solar noon (the time of day at

which the sun is at its highest point in the sky), negative before solar noon, and positive after solar noon. HOMER uses the following equation to calculate the hour angle:

$$\omega = (t_s - 12\text{hr}) \cdot 15°/\text{hr}$$

where: t_s is the solar time [hr]

$$t_s = t_c + \frac{\lambda}{15°/\text{hr}} - Z_c + E$$

The value of t_s is 12hr at solar noon, and 13.5hr ninety minutes later. The above equation follows from the fact that the sun moves across the sky at 15 degrees per hour.
HOMER assumes that all time-dependent data, such as solar radiation data and electric load data, are specified not in solar time, but in *civil time*, also called local standard time. HOMER calculates solar time from civil time using the following equation:

$$E = 3.82\begin{pmatrix} 0.000075 + 0.001868 \cdot \cos B - 0.032077 \cdot \sin B \\ - 0.014615 \cdot \cos 2B - 0.04089 \cdot \sin 2B \end{pmatrix}$$

where: t_c is the civil time in hours corresponding to the midpoint of the time step [hr]
l is the longitude [°]
Z_c is the time zone in hours east of GMT [hr]
E is the equation of time [hr]

Note that west longitudes are negative, and time zones west of GMT are negative as well.
The equation of time accounts for the effects of obliquity (the tilt of the earth's axis of rotation relative to the plane of the ecliptic) and the eccentricity of the earth's orbit. HOMER calculates the equation of time as follows:

where B is given by:

$$B = 360° \frac{(n-1)}{365}$$

where n is the day of the year, starting with 1 for January 1st.

Now, for a surface with any orientation, we can define the angle of incidence, meaning the angle between the sun's beam radiation and the normal to the surface, using the following equation:

$$\cos\theta = \sin\delta\sin\phi\cos\beta - \sin\delta\cos\phi\sin\beta\cos\gamma + \cos\delta\cos\phi\cos\beta\cos\omega + \cos\delta\sin\phi\sin\beta\cos\gamma\cos\omega + \cos\delta\sin\beta\sin\gamma\sin\omega$$

where: q is the angle of incidence [°]
b is the slope of the surface [°]
g is the azimuth of the surface [°]
f is the latitude [°]
d is the solar declination [°]
w is the hour angle [°]

An incidence angle of particular importance, which we will need shortly, is the *zenith angle*, meaning the angle between a vertical line and the line to the sun. The zenith angle is zero when the sun is directly over head, and 90° when the sun is at the horizon. Because a horizontal surface has a slope of zero, we can find an equation for the zenith angle by setting b = 0° in the above equation, which yields:

$$\cos\theta_z = \cos\phi\cos\delta\cos\omega + \sin\phi\sin\delta$$

where: q_z is the zenith angle [°]

Now we turn to the issue of the amount of solar radiation arriving at the top of the atmosphere over a particular point on the earth's surface. HOMER assumes the output of the sun is constant in time. But the amount of sunlight striking the top of the earth's atmosphere varies over the year because the distance between the sun and the earth varies over the year due to the eccentricity of earth's orbit. To calculate the *extraterrestrial normal radiation*, defined as the amount of solar radiation striking a surface normal (perpendicular) to the sun's rays at the top of the earth's atmosphere, HOMER uses the following equation:

$$G_{on} = G_{sc}\left(1 + 0.033\cdot\cos\frac{360n}{365}\right)$$

Where: G_{on} is the extraterrestrial normal radiation [kW/m^2]
G_{sc} is the solar constant [1.367 kW/m^2]
n is the day of the year [a number between 1 and 365]

To calculate the *extraterrestrial horizontal radiation*, defined as the amount of solar radiation striking a horizontal surface at the top of the atmosphere, HOMER uses the following equation:

$$G_o = G_{on} \cos\theta_Z$$

where: G_o is the extraterrestrial horizontal radiation [kW/m^2]
G_{on} is the extraterrestrial normal radiation [kW/m^2]
q_z is the zenith angle [°]

Since HOMER simulates on a time step by time step basis, we integrate the above equation over one time step to find the average extraterrestrial horizontal radiation over the time step:

$$\overline{G_o} = \frac{12}{\pi} G_{on}\left[\cos\phi\cos\delta(\sin\omega_2 - \sin\omega_1) + \frac{\pi(\omega_2 - \omega_1)}{180^\circ}\sin\phi\sin\delta\right]$$

where: is the extraterrestrial horizontal radiation averaged over the time step [kW/m^2]
G_{on} is the extraterrestrial normal radiation [kW/m^2]
w_1 is the hour angle at the beginning of the time step [°]
w_2 is the hour angle at the end of the time step [°]

The above equation gives the average amount of solar radiation striking a horizontal surface at the top of the atmosphere in any time step. The solar resource data give the average amount of solar radiation striking a horizontal surface at the bottom of the atmosphere (the surface of the earth) in every time step. The ratio of the surface radiation to the extraterrestrial radiation is called the clearness index. The following equation defines the clearness index:

$$k_T = \frac{\overline{G}}{\overline{G_o}}$$

Where: G is the global horizontal radiation on the earth's surface averaged over the time step [kW/m^2]
Go is the extraterrestrial horizontal radiation averaged over the time step [kW/m^2]

Now let us look more closely at the solar radiation on the earth's surface. Some of that radiation is *beam radiation*, defined as solar radiation that travels from the sun to the earth's surface without any scattering by the atmosphere. Beam radiation (sometimes called direct radiation) casts a shadow. The rest of the radiation is *diffuse radiation*, defined as solar radiation whose direction has been changed by the earth's atmosphere. Diffuse radiation comes from all parts of the sky and does not cast a shadow. The sum of beam and diffuse radiation is called global solar radiation, a relation expressed by the following equation:

$$\overline{G} = \overline{G}_b + \overline{G}_d$$

Where: Gb is the beam radiation [kW/m^2]
Gd is the diffuse radiation [kW/m^2]

The distinction between beam and diffuse radiation is important when calculating the amount of radiation incident on an inclined surface. The orientation of the surface has a stronger effect on the beam radiation, which comes from only one part of the sky, than it does on the diffuse radiation, which comes from all parts of the sky.

However, in most cases we measure only the global horizontal radiation, not its beam and diffuse components. For that reason, HOMER expects you to enter global horizontal radiation in HOMER's Solar Resource Inputs window. That means that in every time step, HOMER must resolve the global horizontal radiation into its beam and diffuse components to find the radiation incident on the PV array. For this purpose HOMER uses correlation of Erbs et al. (1982), which gives the *diffuse fraction* as a function of the clearness index as follows:

$$\frac{\overline{G}_d}{\overline{G}} = \begin{cases} 1.0 - 0.09 \cdot k_T & \text{for } k_T \le 0.22 \\ 0.9511 - 0.1604 \cdot k_T + 4.388 \cdot k_T^2 - 16.638 \cdot k_T^3 + 12.336 \cdot k_T^4 & \text{for } 0.22 < k_T \le 0.80 \\ 0.165 & \text{for } k_T > 0.80 \end{cases}$$

For each time step, HOMER uses the average global horizontal radiation to calculate the clearness index, then the diffuse radiation. It then calculates the beam radiation by subtracting the diffuse radiation from the global horizontal radiation.

We are now almost ready to calculate the global radiation striking the tilted surface of the PV array. For this purpose HOMER uses the HDKR model, which assumes that there are three components to the diffuse solar radiation: an isotropic component which comes all parts of the sky equally, a circumsolar component which emanates from the direction of the sun, and a horizon brightening component which emanates from the horizon. Before applying that model we must first define three more factors.
The following equation defines R_b, the ratio of beam radiation on the tilted surface to beam radiation on the horizontal surface:

$$R_b = \frac{\cos\theta}{\cos\theta_z}$$

The anisotropy index, with symbol A_i, is a measure of the atmospheric transmittance of beam radiation. This factor is used to estimate the amount of circumsolar diffuse radiation, also called forward scattered radiation. The anisotropy index is given by the following equation:

$$A_i = \frac{\overline{G}_b}{\overline{G}_o}$$

The final factor we need to define is a factor used to account for 'horizon brightening', or the fact that more diffuse radiation comes from the horizon than from the rest of the sky. This term is related to the cloudiness and is given by the following equation:

$$f = \sqrt{\frac{\overline{G}_b}{\overline{G}}}$$

The HDKR model calculates the global radiation incident on the PV array according to the following equation:

$$\overline{G}_T = \left(\overline{G}_b + \overline{G}_d A_i\right) R_b + \overline{G}_d \left(1 - A_i\right)\left(\frac{1+\cos\beta}{2}\right)\left[1 + f \sin^3\left(\frac{\beta}{2}\right)\right] + \overline{G}\rho_g\left(\frac{1-\cos\beta}{2}\right)$$

where: b is the slope of the surface [°]

r_g is the ground reflectance, which is also called the albedo [%]

HOMER uses this quantity to calculate the cell temperature and the power output of the PV array.