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Economic Feasibility Analysis of a Specially Developed Hybrid Roof-Top PV System Under Variable Selected Conditions

A Master's Thesis submitted for the degree of
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Affidavit

I, **Ján Karaba**, hereby declare

1. that I am the sole author of the present Master Thesis, "Economic Feasibility Analysis of a Specially Developed Hybrid Roof-Top PV System Under Variable Selected Conditions",
   62 pages, bound, and that I have not used any source or tool other than those referenced or any other illicit aid or tool, and
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Abstract

The first part of this work undertakes to design and develop a special hybrid roof-top PV system which is capable of operating both in grid-off and grid-on regime. The PV system is developed in single-phase and three-phase configuration utilizing only commercially available technological components. The single-phase configuration is supposed to serve households with low installed power of AC loads whereas the three-phase system is supposed to be supplying electricity to households with high installed power of AC loads. The PV systems are developed in an attempt to maximize the utilization of the systems' energy yield for the self-consumption of the households. In the second part of this work we perform several system energy yield simulations in the HOMER Legacy and PVSYST software tools with the purpose to calculate the expected amount of annual energy produced from the PV systems, the amount of annual energy self-consumed in AC loads and the amount of annual energy sold into the grid. Based on these results and other specifically defined technical and economic inputs we are able to construct an economic valuation model, which subsequently allows us to assess the economic feasibility of both developed hybrid PV systems in the current conditions of Slovakia. According to the results, the single-phase PV system fails to pass the criteria of economic feasibility mainly because of its high investment costs and insufficient level of FiT support. On the other hand, the three-phase PV system proves to be economically feasible even with the existing conditions. We have also performed a sensitivity analysis to explore the future potential of both PV systems being commercially deployed in larger scale.

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1 Introduction

While the first PV cell was developed already in the 1950’s it wasn’t until the beginning of this millennium that energy sources based on PV started to be deployed in larger scale around the world. Indeed, in the last decade PV industry has seen a tremendous and completely unprecedented growth which easily outperformed any other renewable energy sector. To demonstrate the scale of growth in numbers the cumulative installed capacity of grid-connected PV systems jumped from just under 300 MW in 2000 to 67 GW by the end of 2011[1].

One of the main reasons behind this PV boom is certainly the support scheme constituted in the Germany’s Renewable Energy Sources Act which was passed by the German government in 2000. A feed-in-tariff (FiT) mechanism introduced in Germany has since then served exceptionally well as a basic pattern for a majority of other governments who embarked on a road towards higher RES utilization.

The FiT-driven PV market hasn’t turned out to be only a quantitative success but, more importantly, it has led to some major progress milestones. We have seen a severalfold increase in standard crystalline silicon PV cell efficiency, inverter efficiency as well as reliability improvement and thin-film modules successful commercialization.

However, even though we now have a much deeper understanding of PV technologies there are still various largely uncharted areas of PV applications with an arguably high potential of global deployment. This thesis is focused on one of these areas at the centre of which is the effort to design an economically feasible hybrid PV system with grid support.

The current research in the area of hybrid PV systems revolves around two distinctive areas of application: (i) off-grid systems and (ii) mini-grids. Because off-grid (stand-alone) systems have been the focus of numerous scientific studies since the 1980’s several comprehensive design guidelines have been already developed,

[1] data published by European Industry Photovoltaic Association (EPIA), retrieved from http://www.epia.org/fileadmin/EPIA_docs/publications/epia/EPIA-market-report-2011.pdf

such as Chapman (1987), Sandia (1995) or Hansen et al. (2000). On the other hand, the area of hybrid PV systems being used within mini-grids is a fairly new area of research & development and the concept of mini-grids has come under a more intense focus just recently by the International Energy Agency (IEA) that runs a special research program named PVPS Task 11. So far this research has mostly focused on sustainability conditions (Marcel, 2008), grid stability (Espinar & Mayer, 2010) and the survey of available simulation tools (Lippkau, 2008).

The survey of current research in the area of hybrid PV systems is cited here because it provides an important background for the application which is being designed and analyzed in this work.

1.1 Motivation

My motivation for writing this thesis largely reflects my professional interest in PV systems. From 2008 till 2011 I have had the privilege to participate in the development, construction and operation of large-scale ground-mounted PV power plants in Slovakia and the Czech Republic. This year, due to the changes in legislation, the focus has shifted to medium sized (<100 kWp) roof-top PV.

Based on my experience, I can see that as PV technologies mature it is an economic necessity for governments to apply gradual FiT reductions. Seeing this general market trend it is obvious that roof-top PV, utilized mostly for producing electricity to feed buildings' own AC loads, will eventually survive as the only longer-term PV market. In this respect I can see the value of developing an economically feasible commercial product for such a market.

1.2 Defining the core objective

The objective of this work is to analyze the economic feasibility of a specially designed hybrid PV system with respect to a set of variable economic factors: 1) price of electricity, 2) level of FiT support, and 3) investment costs. These three factors were selected precisely because any possible variations in their values have a significant impact on the PV system's economic feasibility and hence its capability of being commercially deployed in a wide scale.

1.3 Citation of main literature

With regards to external source usage it should be pointed out that there are only a limited number of studies and research papers dedicated specifically to the topic of hybridized PV systems with grid support. The notable ones include Sopitpan (2000), Ashraf & Chandra (2004) and Singh & Singh (2010). Although, some of these papers are of somewhat older date they provide a very practical knowledge base for the technical part of this work.

Along with the specifics of hybrid PV system components the process of technical design employed in this work utilizes mostly general PV dimensioning and electrical design guidelines which are in most cases defined by the electrical characteristics of individual system components. The core of the proposed technological solution, which relies on the utilization of Xantrex™ products, is the result of the author's own research & development. In the area of battery storage design the work draws to a certain extent from Hansen et al. (2000).

2 Structure of work and method of approach

This work is logically divided into technical part and economic part. The technical part presents the basic technical design of the proposed hybrid PV system and describes its most important functionalities. This part provides a general description of the characteristics and role for all the below-mentioned technological components working within the PV system:

- PV array
- Bi-directional inverter
- Charge controller
- Battery storage
- AC load panels
- Grid connection & metering

To clearly depict the interaction between all the system's components a comprehensive functional block diagram is elaborated and presented in dual PV system configuration – i.e. single phase and three phase wiring.

The main objective of the technical part is to develop a functional design of the PV system. A particular subtask within the technical design is to find a method of correctly sizing the PV system with regards to the electrical parameters of all utilized components. Furthermore, the technical part presents a commercially available technological solution based on hybrid inverters and charge controllers manufactured by Xantrex™, a subsidiary of Schneider Electric, Inc.. A considerable support for this section was given by the technicians employed at the Slovak office of Schneider Electric who provided access to the latest technical documents regarding their products.

While the technical part of this thesis basically outlines and elaborates on the PV system design it also provides crucial inputs for the second part of the work in which an analysis of PV system's economic feasibility is performed. The first section of this part is concerned with data collection and simulation inputs summarization. Within this, meteorological data for a selected project site are firstly obtained from PVGIS database. Secondly, AC load characteristics for the proposed hybrid system applications are defined. Thirdly, investment and O&M cost parameters are provided for each part of the system. Fourthly, price of electricity and FiT conditions are defined and their possible alterations are accounted for. Using all of the above-mentioned data and inputs a simulation in HOMER Legacy software is performed. The simulation provides an estimated energy yield and self-consumption diagram as well as sensitivity analysis of results. The outcome of the simulation is then used in an economic feasibility assessment whereby standard investment valuation tools are applied. The economic feasibility of the hybrid PV system is valued by three standard investment valuation methods: NPV, IRR and payback period.

The last section of this thesis summarizes the results from its technical and economic part, provides answers to the core objective set in the introduction and offers suggestions for future research goals.

3 Hybrid PV system design

The proposed PV system is designed to meet the following basic functional requirements:

- When grid is stable (i.e. no outage is pending) the system acts as a secondary source of electricity, primary source is grid.
- When grid is unstable (i.e. during grid failures) the system is capable of operating in island mode producing true sine wave as opposed to modified sine wave. The system therefore acts as a primary source of electricity.
- When grid is stable the system operates in grid-on mode in which the energy produced in PV array is used for primary supply of AC loads and secondary supply of grid in case of energy surpluses.
- The system has a battery back-up which discharges during night (supplies night-time AC loads) and charges during daylight when PV array produces energy.

Because the PV system is designed mainly for family houses the technical design must also account for the fact that in some houses the majority of electricity is consumed in single-phase appliances and in other houses where larger AC loads are installed, such as induction cooking coils, air-conditioning units, heat pumps or infrared heating foils, three-phase supply of electricity is required. Given that smaller scale PV inverters (below 10 kVA) are mostly manufactured as single-phase, from this point onward we will be differentiating between single-phase and three-phase configuration of the PV system. The principle of wiring in both cases remains basically the same; the main differences are in the scale, the method of integration of the system within the existing house electrical installation and the grid connection technical requirements.

In the following two chapters related to the PV system's design single-phase and three-phase configurations are presented in a more detailed way.

3.1 Single-phase system

In single-phase configuration several technical points have to be observed. First of all, in most countries there are interconnection standards setting a limit to the maximum power which can be delivered to the grid in single phase. Indeed, local grid operators will typically employ some kind of compliance with international interconnection regulations and standards, such as IEEE 1547[2] and UL 1741[3]. For

[2] IEEE Standard for Interconnecting Distributed Resources with Electric Power Systems, an overview of this document can be downloaded from http://www1.eere.energy.gov/solar/pdfs/15_1547.pdf

instance, in Slovakia this limit is 4.6 kW per phase[4], which translates into nominal current of 20 A at the voltage of 230 V. Subsequently, the power limit for grid injection has an impact on the PV system design in that it sets a cap to the maximum output current of a single-phase grid-connected inverter.

Second of all, because most homes now have three-phase supply of electricity, a single-phase system's injection point must be placed where it will maximize the AC load consumption in the respective phase. This has to be done in the main house switchboard.

Thirdly, and this is directly related to the previous point, in order to maximize the benefit from the hybrid PV system the home electrical installation should, wherever it is possible, connect higher AC loads in the phase which is supplied by the PV system. Obviously this requires an advanced knowledge of the house electrical installation, which can be acquired using an intelligent estimate of the home-owner's consumption behavior or, more accurately, based on results from measuring via a power analyzer.

For a better overview of the single-phase PV system design Figure 1 provides a functional block diagram with the main system components.

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[3] published by Underwriter Laboratories, the scope of the standard can be retrieved from http://ulstandardsinfonet.ul.com

[4] based on the currently valid technical conditions of the grid operator ZSE-Distribúcia, a.s. retrieved from http://www.zse.sk/index.php?www=sp_file&id_item=1019, p. 109

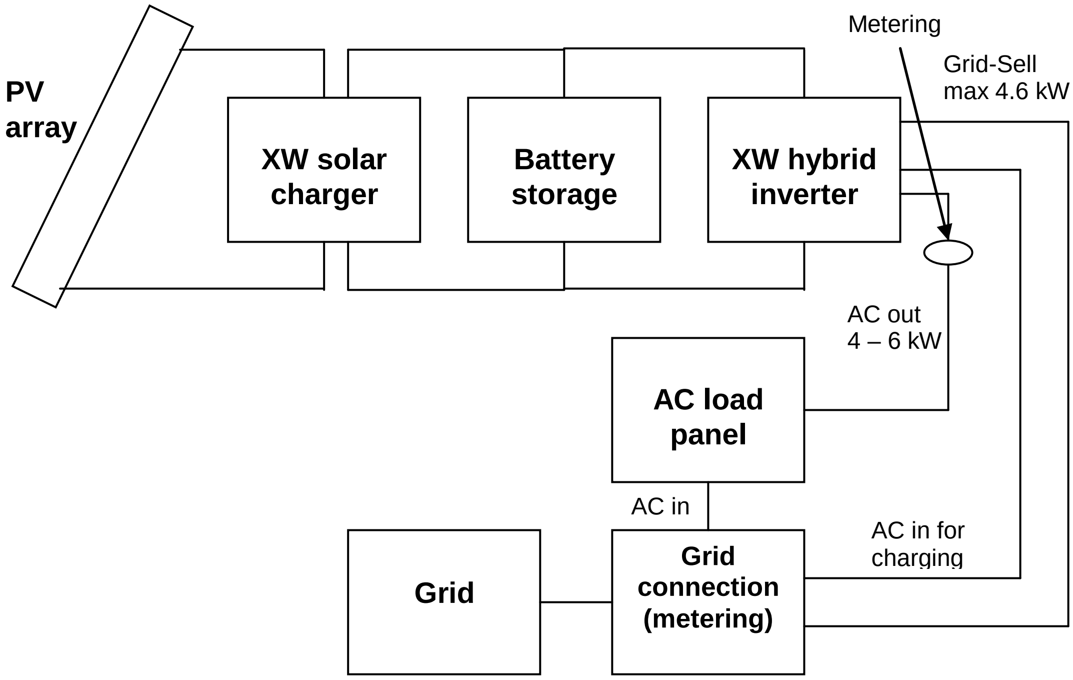

FIGURE 1 Functional diagram of a single-phase hybrid PV system

3.2 Three-phase system

In principle, a three-phase configuration of the PV system is just a more complicated version of the single-phase design. The main difference is in the total grid-connectible AC output power which will typically be limited by the grid operator only based on a calculation of free capacity in the grid at the particular injection point. In some cases, such as when the grid operator's distribution transformer is positioned nearby, this means that the free capacity in the grid should be always higher than the maximum possible installed PV power on the particular house roof, which is limited by the roof size. In other cases, such as when the grid injection point is located at the end of the electrical line the PV system power output to the grid could still be restricted. For this reason the PV system should be able to set a maximum power permissible for the grid delivery.

The second difference is related to the number of system components required to make the three-phase system work. Due to the fact that to produce a three-phase current at least three single-phase inverters (for each phase) have to be used, this configuration also needs at least three separate solar chargers and PV arrays. As a matter of fact, several inverters can be connected in parallel for each phase in order to achieve higher AC power. However, when more inverters are used to produce three-phase current the function of frequency synchronization must be secured to avoid phase-decoupling. Thus the inverters must be connected with each other by a communication cable.

For a better overview of the three-phase PV system design Figure 2 provides a functional block diagram with the main system components.

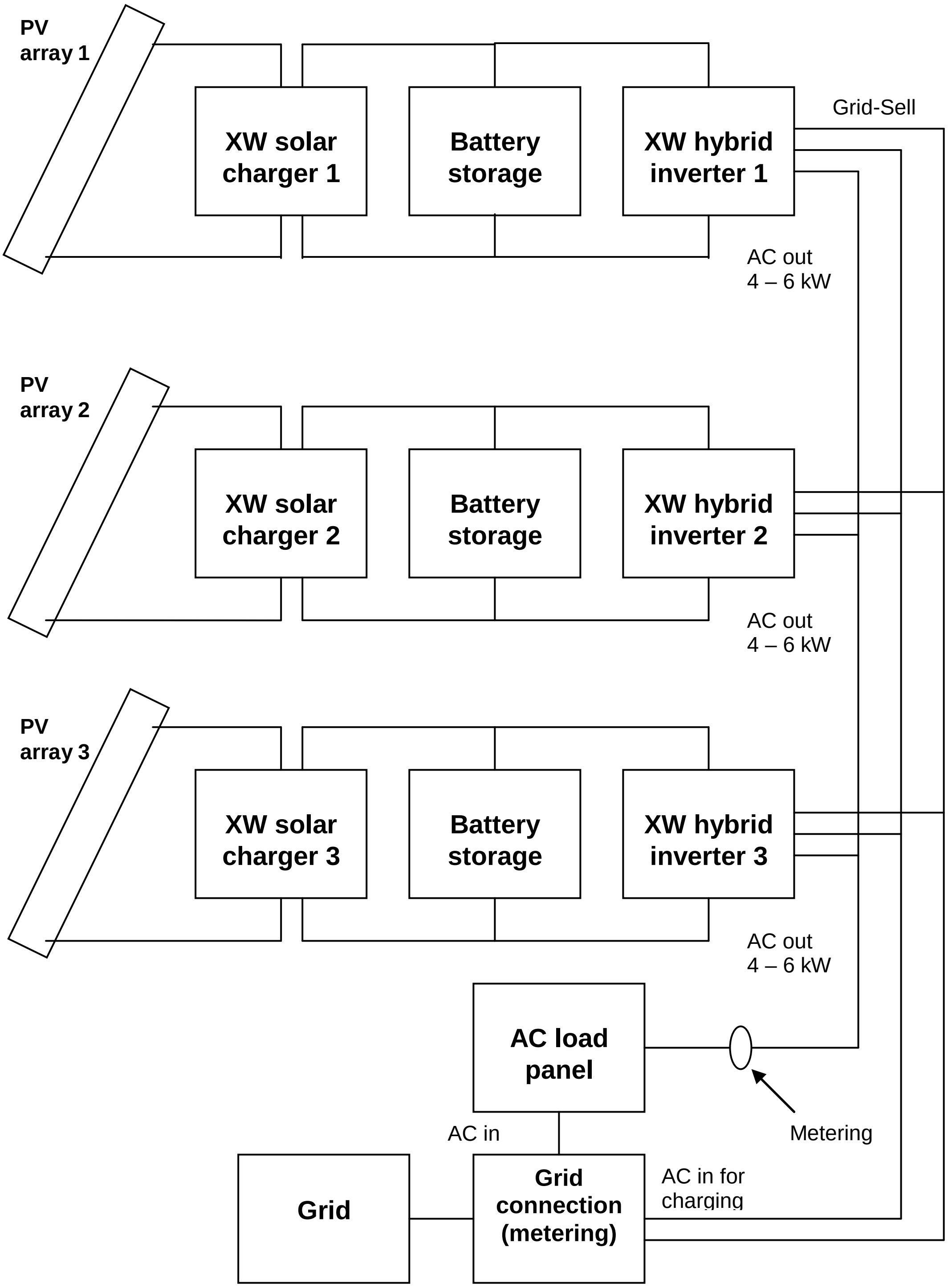

FIGURE 2 Functional diagram of a three-phase hybrid PV system

3.3 System components

The hybrid PV system basically comprises a PV array, charge controller with an integrated MPP tracker, battery storage which charges up during day and discharges during night, bi-directional inverter for DC-AC as well as AC-DC conversion, AC load panel which plugs into the house electrical installation, and a grid connection switchboard with metering. To complete the schematic view of the PV system depicted in Figure 1 and Figure 2 this section provides a more detailed description of the individual system components' functions. It also explains why certain technological alternatives work better within the PV system and why others are not so suitable.

3.3.1 Solar charger with MPP tracker

Solar charger with MPP tracker and hybrid inverter represent the core functions of the PV system, as they were explained at the beginning of this chapter. In this section we will analyze in more detail the solar charger's functions and properties. The system design utilizes a product originally developed by Xantrex Technology, Inc. and currently manufactured by Schneider Electric which acquired Xantrex Technology in 2008. Table 1 below enlists the principal electrical properties of the selected device type.

TABLE 1 Electrical parameters of the XW MPPT 80 600 solar charger [source: Schneider Electric[5]]

Maximum PV Array Open Circuit Voltage	600 VDC
PV Array Voltage Operating Range	195 to 550 VDC
PV Array Voltage Full Power Range	230 to 550 VDC
Maximum Power Point Tracking Range	195 to 510 VDC
PV Array Start Voltage	230 VDC
PV Input Current Limit	23 ADC (electronically limited)
Maximum Permissible PV Short Circuit Rated Current	28 ADC @ STC
Nominal Battery Voltages	24 and 48 VDC (Default is 48 V)
Battery Voltage Operating Range	16 to 67 VDC
Maximum Charging Current	80 A
Maximum Charging Power	2560 W (nominal 24 V battery bank)
	4800 W (nominal 48 V battery bank)
Maximum Power Conversion Efficiency	94% (nominal 24 V battery bank)
	96% (nominal 48 V battery bank)

[5] Schneider Electric: "Xantrex XW MPPT 80 600 Installation Guide (Revision A)", November 2010

Auxiliary Output	Dry contact switching up to 60 VDC, 30 VAC, 8 A
Charger Regulation Method	Three stage (bulk, absorption, float)
Two stage	(bulk, absorption)

Essentially the XW solar charger combines two functions necessary for power generation of the PV system: 1) maximum power point tracking (MPPT) of the PV array and 2) charging optimization of battery storage devices. When batteries are fully charged all the power from the PV array is delivered directly to the hybrid inverter. The MPPT function allows the XW charger to obtain maximum available energy from the PV array using an algorithm which continuously seeks the maximum power point. The function is illustrated in Figure 3.

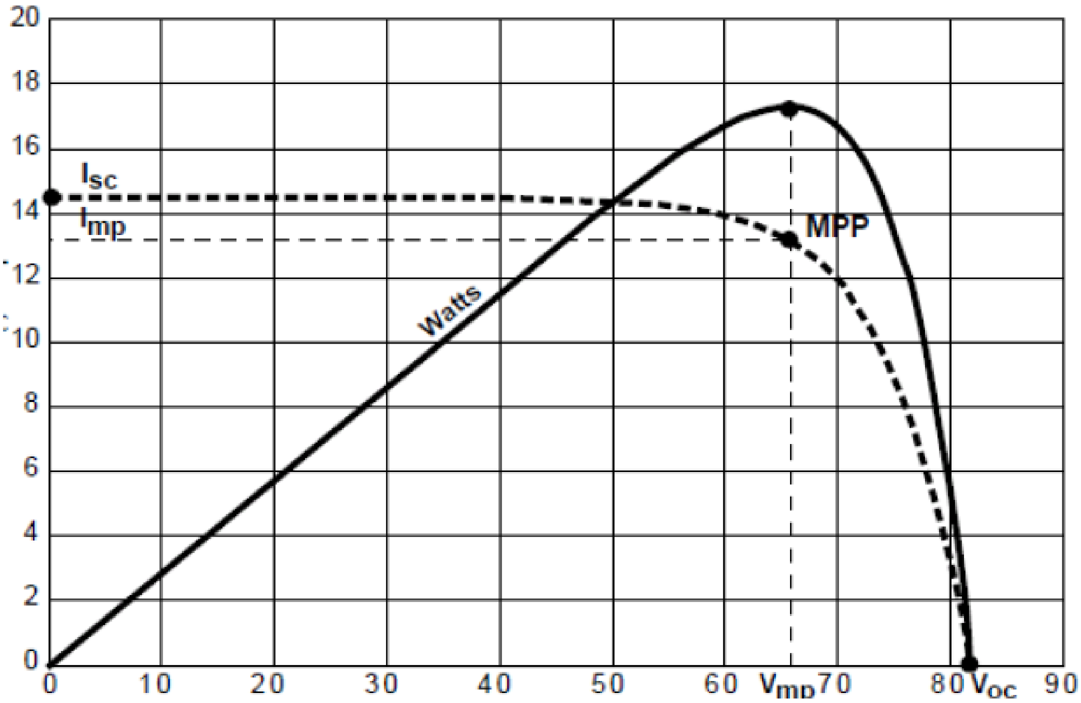

FIGURE 3 Graph illustrating the tracking of maximum power point (MPP) [source: Schneider Electric[6]]

The XW charger can be used to charge battery systems with 24 or 48 V DC with a maximum charging power of 4800 W. According to the manufacturer's installation guide the PV array is allowed to have a maximum nominal power of 13800 W, based on the assumption of 600 Voc x 23 A. The XW charger also has the ability to operate in 2 or 3 stage charging mode, which is designed to reduce the gasification of batteries and minimize losses in the battery electrolyte. Furthermore, a special battery temperature sensor (BTS) can be connected to the charger to perform

[6] ibid

temperature compensation for battery charging. Battery charging changes electrical properties with variable temperature. Therefore it's important to adjust the charging voltage and current according to actual conditions of the battery storage. To ensure that battery charging works optimally the XW charger must be configured according to the individual PV array (input) and battery storage (output) parameters before it is put into use.

All in all, we can see that the selected solar charger is in fact a quite sophisticated device with advanced functions designed to meet the requirements of efficient delivery of DC into the battery storage from where it can supply the hybrid inverter. Because these two devices basically work in unison they must be connected via a special communication cable termed as Xanbus™.

3.3.2 Hybrid inverter

While the XW solar charger described in the previous section already combines several technologically advanced functions the hybrid inverter is by definition an even more complicated device. In fact, there are three distinct functions that the inverter must be capable of performing: 1) convert DC into AC when batteries discharge (i.e. regulate discharging), 2) convert DC into AC when batteries have full capacity and thus power AC loads, and 3) convert AC into DC to charge batteries from the grid (i.e. regulate charging). Of course, when we refer to AC here we really mean AC with a frequency (sine wave) that is synchronized with the grid.

For our PV system design a special hybrid inverter was selected, which was originally developed by Xantrex Technology, Inc. and is now manufactured by Schneider Electric, same as the XW charger. Currently there are three types of commercially available XW hybrid inverters with various output power. Table 2 below summarizes and compares their electrical properties.

TABLE 2 Electrical parameters of XW hybrid inverters [source: Schneider Electric[7]]

Type code	XW6048-230-50	XW4548-230-50	XW4024-230-50
Permanent output power	6000 W	4500 W	4000 W
Peak power	12000 W (15s)	9000 W (20 s)	8000 W (20 s)

[7] downloaded from http://www2.schneider-electric.com/corporate/en/products-services/renewable-energies/renewable-energies-intermediate.page?f=F13%3ASolar~!NNM1:Solar+Backup+and+Off-Grid+Systems&p_function_id=5099

Surge current	53 A ef.	40 A ef.	35 A ef.
Wave form	true sine wave	true sine wave	true sine wave
Maximum efficiency	95,40%	95,60%	94,00%
Consumption in stand-by mode	< 7 W	< 7 W	< 7 W
AC connection	AC1 (grid), AC2 (generator)	AC1 (grid), AC2 (generator)	AC1 (grid), AC2 (generator)
Range of input AC voltage	165 to 280 V AC (230 V nominal)	166 to 280 V AC (230 V nominal)	167 to 280 V AC (230 V nominal)
Range of input AC frequency	40 to 68 Hz (50 Hz nominal)	41 to 68 Hz (50 Hz nominal)	42 to 68 Hz (50 Hz nominal)
Output AC voltage	230 V +/- 3 %	230 V +/- 3 %	230 V +/- 3 %
Maximum passing current	56 A	56 A	56 A
Permanent output AC current	26,1 A	19,6 A	17,4 A
Output AC frequency	50 Hz +/- 0,1 Hz	50 Hz +/- 0,1 Hz	50 Hz +/- 0,1 Hz
Total harmonic distortion	< 5 % of nominal power	< 5 % of nominal power	< 5 % of nominal power
Typical transient time	8 ms	8 ms	8 ms
DC current at nominal power	131 A	96 A	178 A
Range of input DC voltage	44 to 64 V	44 to 64 V	22 to 32 V
Permanent charging current	100 A	85 A	150 A
Power factor correction for charging	0,98	0,98	0,98
Nominal input DC voltage	50,4 V DC	50,4 V DC	25,2 V DC
Supported battery types	Flooded (default), AGM, Gell, user defined		

As we can see, the differences between the listed XW inverter types are not just in the available AC power but also in their maximum efficiency and in the range of input DC voltage. In fact, the XW4024 inverter has the lowest efficiency and can handle only batteries with a maximum voltage of 32 V. This, of course, poses some limitations on the XW charger and battery storage dimensioning.

As it happens, the XW inverters are one of the few commercially available inverters which can operate both in grid-off and grid-on mode. In practice this means that whenever there is a disturbance in the grid[8] the inverter can be configured to automatically assume the role of a main electricity source. Because switching from grid-on to grid-off mode takes only 8ms (i.e. transient time) the vast majority of household appliances will not even notice the change. Moreover, for a small period of times the XW inverter is capable of delivering surge current which is two times higher than the nominal current. This is especially important for more demanding devices, such as pumps, refrigerators or A/C compressors that require more power

[8] The disturbance may result from over/under voltage, under/over frequency, frequency asymmetry or when grid is completely down during servicing, something being damaged or in case of a failure of grid technical devices (e.g. substation, distribution transformer, etc.)

at the start. On the other hand, when the XW inverter suffers a breakdown it has an integrated AC bypass relay which makes all the power from the grid pass to all the household AC loads.

One of the inverter's main functions is the Grid Support and Grid Sell mode, which enable the PV system to feed surplus power into the grid when the output power is greater than the household AC loads demand. The feeding of surplus power to the grid is active only when the battery voltage is higher than a pre-configured value. An interesting feature of the Grid Sell mode is the ability to set maximum level of current for delivery of power to the grid.

Although in this work we treat the PV array as the only power generator in the system it should be noted that the XW inverter also supports other electricity sources, such as diesel generator, small hydropower plant or wind turbine. These can be plugged into a separate AC input (denoted as AC2 in Table 2) of the inverter's distributor box. Thus the inverter is capable of operating with DC as well as AC power sources at the same time.

With all of the above-mentioned functions it's obvious that the XW inverter plays the core role in the whole PV system design. Not only does it convert DC into AC (main function), which can then be used to power AC loads, but it also facilitates the interaction between the PV system's DC side and the grid. Thus the inverter effectively controls the level of the PV system's grid support and regulates the distribution of output power between AC loads on the one side and the grid on the other side. This is why the XW inverter is also perfectly capable of supporting smart grid technologies.

3.3.3 PV array

The power generator in the hybrid PV system is represented by a PV array – i.e. a special wiring of PV modules designed to produce desired output voltage and current. The wiring has to be designed according to the device which utilizes the produced power – in this case it is the XW charger with an integrated MPP tracker.

The XW charger's electrical characteristics determine that the output from the PV array mustn't exceed Vmpp = 550 V and Voc = 600 V with regards to voltage, and Isc = 28 A with regards to current. Because in a serial (string) connection voltage compounds and current doesn't whereas in parallel connection current compounds and voltage doesn't, we need to design PV module strings with regards to the input Vmpp required by the charge controller. This practically means that a distributor has to be used for combining several strings into one cable with lower voltage and higher current.

3.3.3.1 Mono-crystalline modules

PV modules based on mono-crystalline silicon (mono-Si) cells was how the PV industry started in the 1950's. Since then the conversion efficiencies of mono-Si modules have climbed up to a currently standard level of around 16% while the highest efficiency modules reach a conversion efficiency of 22%. However, even though these high efficient modules are available on the market their price tends to be considerably higher than that of the standard modules. Due to the substantial price difference these high-efficiency modules will not be considered in the technical design. We will rather analyze the possible use of mono-Si PV modules with standard conversion efficiencies, which have typical characteristics, as outlined in Table 3 below.

TABLE 3 Basic properties of a mono-Si PV module labeled as FE-260M [source: PV module datasheet[9]]

Nominal maximum power at STC (Pmax)	260 W	
Optimum operating voltage (Vmpp)	51.00 V	
Optimum operating current (Impp)	5.10 A	
Open circuit current (Voc)	61.00 V	
Short circuit current (Isc)	5.51 A	
Operating temperature	45 +- 2°C	
Maximum system voltage	1000 V	
Power tolerance	+- 3%	
Temperature coefficient	Pmax	-0.37 %/°C
	Voc	-0.037 %/°C
	Isc	-0.34 %/°C
	NOCT	-0.37 %/°C
Cell type	mono-crystalline 125 x 125 mm	
Cell arrangement	96 (8 x 12)	
Dimensions	1580 ×1062 ×45 mm	
Weight	22 kg	

As we can see in Table 3 standard mono-Si modules have a relatively higher Vmpp and lower Impp. With respect to the maximum permissible inputs of the solar charger and taking into account the power coefficient we can allow no more than 9 modules per string with a maximum of 4 strings in parallel connection. This means

[9] available at http://www.fire-energy.net/own/pvpanels/datasheets/

that the maximum nominal installed power of the PV array connected to 1 MPPT charger is 4 x 9 x 260 W = 9360 W.

3.3.3.2 Multi-crystalline modules

Compared to mono-Si PV modules multi-crystalline silicon PV modules (mc-Si) have lower conversion efficiencies - currently ranging from 14 to 15.5 %. However, this disadvantage is compensated by their price, which is nowadays lower than mono-Si mainly because the global production of poly-silicon, as the key material input, has greatly increased in the recent years. Consequently this has pushed the costs of making mc-Si modules down. From the electrical standpoint a typical mc-Si module has characteristics summed up in Table 4.

TABLE 4 Basic properties of a multi-Si PV module labeled as CS6-250P [source: PV module datasheet[10]]

Nominal power at STC (Pmpp)	250 W	
Optimum operating voltage (Vmpp)	30.1 V	
Optimum operating current (Impp)	8.30 A	
Open circuit current (Voc)	37.2 V	
Short circuit current (Isc)	8.87 A	
Operating temperature	-40°C - +85°C	
Maximum system voltage	1000 V	
Power tolerance	0 ~+5 W	
Temperature coefficient	Pmax	-0.43 %/C
	Voc	-0.34 %/C
	Isc	-0.065 %/C
	NOCT	45 +- 2°C
Cell type	poly-crystalline 156 x 156 mm	
Cell arrangement	60 (6 x 10)	
Dimensions	1638 ×982 ×40 mm	
Weight	20 kg	

As opposed to their mono-Si rival mc-Si modules have a lower voltage and higher current. This means that it will be possible to connect more modules into a string but there will be fewer parallel connections. Indeed, according to the recommendation from Schneider Electric 12 modules are allowed per string with a maximum of 2 strings in parallel connection. This gives us a maximum PV array's nominal installed power of 6000 W connected to 1 MPPT charger.

[10] available at http://www.canadiansolar.com/en/products/standard-modules/cs6-series.html

3.3.3.3 Thin-film modules

Thanks to the last decade's technological improvements in PV technologies, traditional crystalline PV modules have been enlarged by a new area of PV conversion technologies which can be summed up under the term "thin-film". This includes such technologies as amorphous silicon (a-Si), cadmium telluride (CdTe) copper indium gallium selenide (CIGS or CIS), dye-sensitized solar cell (DSC) along with their respective derivatives. CdTe technology in particular has been winning the thin-film battle lately with very low production costs and relatively high conversion efficiencies. Table 5 below summarizes the most important properties of a typical CdTe PV module, which was selected as a representative of thin-film technologies.

TABLE 5 Basic properties of a thin-film CdTe PV module labeled as FS-275 [source: PV module datasheet[11]]

Nominal power (Pmpp)	75 W	
Optimum operating voltage (Vmpp)	69.4 V	
Optimum operating current (Impp)	1.08 A	
Open circuit current (Voc)	92.00 V	
Short circuit current (Isc)	1.20 A	
Operating temperature	N/A	
Maximum system voltage	1000 V	
Power tolerance	+- 5%	
Temperature coefficient	Pmax	-0.25 %/C
	Voc	-0.25 %/C
	Isc	+0.04 %/C
	NOCT	45 +- 2°C
Dimensions	1200 ×600 ×6.8 mm	
Weight	12 kg	

We can see that CdTe PV modules are characterized by a high voltage and very low current level. Actually this is typical for all other thin-film technologies. That's why string dimensioning using these modules is often more challenging compared to crystalline modules. In case of the above-mentioned First Solar module the sizing allows for only 6 modules per string with 19 strings connected in parallel. However, this is a very inconvenient string design for the following reasons:

- Higher quantity of solar cables is required because each module must be connected to a string distributor by two separate + and – cables.
- Additional surge guards are necessary to ensure that each string is protected against overvoltage on the output side; this also means that string distributors will be larger and therefore more costly.

[11] available at http://atn-engineering.squarespace.com/storage/FS_English.pdf

When the above-mentioned disadvantages are combined with the fact that most thin-film modules are frameless and therefore require a more complicated mounting structure we can conclude that thin-film PV modules are not a suitable alternative for the PV array of our hybrid PV system. On the whole, mc-Si modules offer the best price/performance ratio even though they cannot boast with the highest of efficiencies.

3.3.4 Battery storage

In principle a battery is a "product which consists of one or more electrochemical cells, electrically connected in an appropriate series / parallel arrangement to provide the required operating voltage and current levels, including, if any, monitors, controls and other ancillary components" (Linden & Reddy, 2002). Battery is an integral part of the PV system design and is connected between the XW charger and the XW hybrid inverter. The former one charges the battery storage from the PV array during daylight while the latter one discharges the batteries when power for AC loads is needed and there is insufficient irradiation outside, which is typically during night. Due to this specific pattern of charge/discharge regime the PV system can only utilize what is called as 'deep-cycle batteries'. Deep-cycle batteries belong to a category of stationary batteries that are designed for such applications as load leveling, utility peak-power shaving and renewable energy storage. The most important requirements to be looked for in stationary batteries are high cycle life, high energy density (Wh/L), and low cost. This is why stationary batteries use mostly lead-acid cells with heavy, thick positive and negative plates and high paste density. These cells have a typical useful life between 1000 and 2000 cycles at Depth of Discharge[12] (DoD) of 80% at a cost of under 100 $/kWh (Linden & Reddy, 2002). However, the deeper the batteries are discharged, the shorter their cycle life. The critical level of DoD in most deep-cycle batteries is 80% above which the batteries start loosing capacity much more rapidly.

Lead-acid stationary batteries for deep-cycle applications employ three basic designs: 1) conventional flooded cells (also known as VLA), 2) absorbent electrolyte and 3) gell electrolyte - the latter two are also known as valve regulated lead-acid

[12] This is a technical term commonly used for stationary batteries, which indicates the ratio of capacity (in %) discharged from a fully charged battery. For deep-cycle applications a certain DoD corresponds to a number of cycles of charging/discharging that the battery can sustain in its technical lifetime

(VRLA) batteries. These three battery designs are supported by the XW charger as well as the XW hybrid inverter. In the following subchapter we will analyze their main features with the aim to select the most suitable type for our PV system application.

From the wiring point of view, the electrical parameters of the XW charger and the XW hybrid inverter determine just how the battery storage has to be connected. The XW charger supports a maximum battery voltage of 60 V DC while the XW hybrid inverters can handle up to 64 V DC of battery output voltage (except XW4048, which is limited to 32 V DC). This means that the battery system will be made of a serial connection of cells with a compound voltage of up to 60 V DC. Moreover, if more XW chargers are used in the PV system (as is the case in the three-phase design) it is necessary to have equal number of parallel battery connections. A functional scheme of this serial-parallel connection is shown in Figure 4.

3.3.4.1 Comparison of VLA and VRLA batteries

Flooded cell batteries (VLA) represent the conventional stationary battery design. They are not sealed and their whole electrolyte content freely floods the positive and negative plates inside the cells. There is nothing to prevent the escape of hydrogen and oxygen gases normally lost during charging and discharging, which is why they require regular watering. Also, due to the lack of seal VLA batteries always have to be kept in upright position to avoid any leakages of electrolyte. However, VLA batteries have proven to be reliable, relatively inexpensive with long lifetime. They can also endure higher temperature differences.

Absorbent electrolyte batteries (AGM) belong to a category of valve regulated lead-acid batteries (VRLA) and have the electrolyte absorbed in a fiber-glass mat separator reservoir. Gel cell batteries also belong to the VRLA batteries because of the way gasses are vented inside the cells. The electrolyte is enriched by fumed silica which causes it to harden into a gel. This allows batteries to be installed and kept in different orientations without the risk of electrolyte leakage. The main advantage of VRLA batteries consists in their “maintenance-free” design, which refers to the fact that there is no need to replace electrolyte. However, there are also considerable disadvantages to their use. Table 6 provides a comprehensive comparison of VLA and VRLA batteries.

TABLE 6 Schematic comparison of VLA vs. VRLA batteries [source: Linden & Reddy (2002), Clark, M.S. (2008) and Rusch et al. (2006)]

	Flooded (VLA)	AGM (VRLA)	Gel (VRLA)
Reliability	high	moderate	moderate
Cycle life (at 80% DoD)	high	moderate	high
Energy density	moderate	low	low
Charging efficiency	moderate	high	high
Inner resistance	low	moderate	high
Maintenance	high	low	low
Storage requirements	high	moderate	moderate
Thermal run-away	low	high	low
Cost	low	moderate	high

According to the comparison of VLA and VRLA batteries it appears that VLA batteries are better on all accounts except maintenance (constant watering) and storage requirements (risk of electrolyte leakage). On the other hand, when we compare AGM to Gel batteries are AGM clearly have either similar or worse-off properties except their cost. To decide which battery technology is the most suitable we have to run the compared characteristics through several assessment criteria listed in the following order of importance: (i) cycle life, (ii) cost, and (iii) maintenance. The criteria were selected in this precise order because cycle life and cost have the biggest impact on the overall economics of the back-up storage system while maintenance makes a relatively small component of O&M costs (see chapter 4.1.6). From this point of view, we can conclude that VLA batteries stand as a more suitable technological alternative for the PV system design, right after Gel VRLA batteries. However, in individual cases when the cost difference between VLA and Gel cell batteries is not so significant, Gel batteries could provide a better value because they require much lower maintenance and have a higher charging efficiency. Also, Gel batteries will probably provide a better value when there is a high risk that the owner of the PV system could neglect watering of VLA batteries, which might result in their significant deterioration and hence the overall economics.

3.3.5 AC load panel

Because our hybrid PV system is designed to primarily power the AC loads installed in a household the output power from the XW inverter must be connected to an existing electrical installation which delivers power to individual AC loads. For this purpose the PV system can utilize an existing AC load panel (i.e. main house distributor) or the existing load panel is replaced with a new one which will enable to integrate the PV system within the house electrical installation. For obvious reasons the AC load panel will have different properties when a single-phase or three-phase

PV system is connected. Apart from mandatory surge guards (one for each phase of the PV system power output) the AC loads panel can also have special contactors through which powering of selected AC load circuits can be performed. This way when a grid malfunction occurs and the PV system operates in grid-off mode the powering of AC loads can be regulated in a pre-selected order of importance – e.g. lighting, electronic security system, personal computers, etc.

3.3.6 Grid connection and metering

As it was mentioned at the beginning of this chapter a parallel source of electricity connected to the grid must comply with the grid operator's interconnection standards. Perhaps the greatest concern in this respect is the issue of islanding, which refers to such a condition when "a distributed generator (DG) continues to power a location even though electrical grid power from the electric utility is no longer present" (Bower & Ropp, 2002). For this reason, and despite the fact that most DG's capable of operating in grid-off mode already have an anti-islanding detection measure, the grid operator will typically require some kind of additional external device that will switch down the grid supply of power from a DG when the grid is down. For this purpose it is usually required to use a motor driven main switch which is actuated either by a simple electrical relay set to react on basic faulty conditions or a more sophisticated digital protection which has more functions and its reactions are more precise. In case of a single-phase AC power output a relatively simple single-phase relay reacting to under/over voltage will be sufficient. As for the three-phase system, the grid operator will typically require a special three-phase grid protection against under/over frequency and under/overvoltage. In any case, the grid protections must be connected before the main AC grid supply switch and should either be a part of the AC load panel if the grid supply switch is located here as well or should be placed inside the main supply cubicle if it is located somewhere else.

As for the metering, there are two issues that have to be taken into account. Firstly, in most cases for grid supply of power from the PV system the existing electricity meter should be replaced by a new one that can also meter supplied kWh's. When net metering policy is valid in the given country or region, such as the one constituted by the Energy Policy Act of 2005 in the USA, smart meters will likely be used to replace the old electricity meters. Secondly, some countries like Germany, Czech Republic or Slovakia have special feed-in tariff support schemes with bonuses for electricity produced and consumed in the same place. These incentives make for the need to also measure the produced electricity right on the output from the PV system – i.e. on the terminal of the AC output of the XW hybrid inverter in this case.

4 Economic feasibility analysis

Based on the first part of this work in which we discussed technical properties of the proposed hybrid PV system we will now proceed to perform an economic feasibility analysis. The analysis will be conducted in several stages. First of all, we have to define the right inputs for the simulation in HOMER Legacy[13] as well as PV SYST 5.56[14]. According to Arribas et al. (2011) these are two of the most recommended energy modeling software packages developed especially for renewable energy systems.

4.1 Simulation inputs

Apart from the technical properties already explained in the first part of this work we will also have to define reliable data about solar irradiation, define AC loads and consumption regimes. Furthermore, we will describe the FiT support conditions; define the price of electricity, investment and O&M costs according to the hybrid PV system design. Consequently, using these inputs we will run a simulation in both selected software packages with the intention to obtain the following results: 1) total energy produced from the PV system (on the AC output of the inverter), 2) energy produced and consumed by AC loads, and 3) energy produced and supplied to the grid as a surplus over AC load consumption. Once we have these results we can start evaluating the economic feasibility of the PV system using standard investment valuation methods such as NPV, IRR and payback time.

4.1.1 Meteorological inputs

Arriving at reliable energy yield results requires in the first place reliable meteorological inputs. For HOMER Legacy program we will need to define namely the global irradiation at horizontal plane parameter and the Clearness index. PV SYST, on the other hand, uses the global and diffuse irradiation at horizontal plane

[13] available to download from http://www.homerenergy.com/

[14] available to download from http://www.pvsyst.com/

and the temperature parameters. Because both programs require average monthly values of these meteorological inputs we will have to find a reliable source of such refined data. In order to obtain good inputs the following approach will be employed:

1. Selection of the PV system geographical location (i.e. GPS coordinates)
2. Selection of suitable and accessible database/s
3. Calculation of average monthly values
4. Normalization of calculated results

For the purposes of the feasibility analysis a location for the hybrid PV system was selected in Bratislava, Slovakia at a place with these specific GPS coordinates: 48.163 N, 17.060 E. In the second step several databases were evaluated as possible sources of required meteo data. Based on the suggestions made by PVSYST[15] the following databases were selected for final data calculations: PVGIS[16] run by Joint Research Centre of the European Commission and Meteonorm[17] produced by the company METEOTEST. These databases were chosen because they offer the desired categories of long-term data (global irradiation, diffuse irradiation, temperature and wind speed) and because the data are available for the latest historical period (up to 2005).

After having entered the GPS coordinates of the selected PV system location, the calculation in PVSYST and Meteonorm provided average values of required parameters which are presented in Table 7 below. The Gh and DGh parameters stand for average values of global irradiation at horizontal plane (in kWh/m2/day) and global diffuse irradiation at horizontal plane (in kWh/m2/day) respectively, the Ta parameter represents average daily temperature (in °C), and the Clearness Index represents a dimensionless number calculated from the Gh parameter (the calculation was performed directly in the PVSYST program).

TABLE 7: Results of meteo data calculation in PVGIS and Meteonorm

Database	**PVGIS**				**Meteonorm**			
Month	Gh	DGh	Ta	Clearness	Gh	DGh	Ta	Clearness
Jan	0,92	0,62	-0,1	0,32	0,84	0,52	-1,6	0,29
Feb	1,62	1,00	2,6	0,36	1,68	0,96	0,8	0,37

[15] see http://www.pvsyst.com/en/publications/meteo-data-sources

[16] http://re.jrc.ec.europa.eu/pvgis/apps4/pvest.php#

[17] available at http://meteonorm.com

Mar	2,79	1,59	6,8	0,42	2,74	1,58	5,4	0,42
Apr	4,24	2,16	13,0	0,47	4,17	2,47	9,7	0,47
May	5,28	2,69	18,1	0,49	5,48	2,55	14,1	0,51
Jun	5,67	2,89	21,0	0,49	5,83	2,77	17,3	0,50
Jul	5,80	2,67	22,7	0,52	5,68	2,61	19,3	0,51
Aug	4,84	2,37	22,5	0,50	4,90	2,26	18,9	0,50
Sep	3,55	1,74	18,0	0,47	3,40	1,77	15,3	0,45
Oct	2,22	1,20	13,1	0,42	2,16	1,23	10,1	0,41
Nov	1,06	0,71	6,7	0,32	0,97	0,67	4,6	0,29
Dec	0,68	0,50	0,8	0,28	0,65	0,45	-0,3	0,27

We can see that there are only minor differences between the values obtained from the PVGIS and Meteonorm database. It is therefore difficult to reason which data are more suitable and reliable as meteo inputs. On the other hand, if we were to utilize the results of both databases, it is convenient to make arithmetic averages from all the sets of values. The results of this operation are shown in Table 8 and will be used as the ultimate meteo inputs for the simulation in HOMER Legacy as well as PVSYST.

TABLE 8: Calculation of arithmetic averages of meteo data [source: author's own calculations]

Month	Gh	DGh	Temp.	Clearness
Jan	0,88	0,57	-0,85	0,31
Feb	1,65	0,98	1,70	0,37
Mar	2,77	1,59	6,10	0,42
Apr	4,20	2,31	11,35	0,47
May	5,38	2,62	16,10	0,50
Jun	5,75	2,83	19,15	0,50
Jul	5,74	2,64	21,00	0,51
Aug	4,87	2,31	20,70	0,50
Sep	3,48	1,75	16,65	0,46
Oct	2,19	1,21	11,60	0,42
Nov	1,01	0,69	5,65	0,31
Dec	0,66	0,48	0,25	0,27

4.1.2 AC load profiles

At this point we will proceed to define the AC load profiles of self-consumption powering of which is the primary goal of the hybrid PV system. Because of the dual possible configuration of the PV system (i.e. single-phase and three-phase) we will define AC load profiles separately for a house with relatively low power consumption of appliances, most of which utilize single-phase current, and a house with a relatively high power consumption with several appliances with three-phase current requirement. In the process of defining the AC load profiles one has to take into account the following facts:

1. Because most house appliances are not utilized constantly we will have to introduce a special 'coefficient of utilization' representing the average usage of appliances over a pre-defined time period.
2. Some appliances, such as heat-pump or air-conditioning, clearly have different load profiles in different seasons. This is largely based on the geographical location of the house and its climate conditions. To account for these differences seasonal adjustments have to be implemented.
3. AC load profiles are different during day-time hours (7.00 – 22.00) and night-time hours (22.00 – 7.00). The same is true for morning/evening peaks in comparison to standard work-time hours.

The above-mentioned facts will also have a major effect on the battery storage dimensioning, which will be performed in the following steps:

1. Calculation of the required energy for the energy consumption during night-time hours.
2. Decision about the optimal level of DoD – we will assume a DoD of 60% to achieve a reasonable compromise between the battery size (and hence the cost) and its cycle life-time.
3. Decision about the battery cell type and ampere-hour (Ah) capacity.

Because the battery storage functioning within the hybrid PV system is not intended to cover 100 % of possible night-time electricity consumption we will not provide for a reserve storage capacity for longer peak occurrences. The PV system will be configured in such a way that when the battery reaches DoD of 60% the XW inverter will automatically switch off the energy supply from the battery and all the AC loads will be powered from the grid.

4.1.2.1 Low consumption house

For the sake of our feasibility analysis a low consumption house is defined as one which includes only AC loads with low installed power, all of which can thus be running on single-phase AC. Table 9 provides a list of assumed AC appliances together with their coefficients of utilization (denoted as ß) for daytime and night-time usage. The role of a coefficient of utilization is to adjust the power consumption to the fact that the AC appliance uses its nominal installed power only part of its running time. For instance, although a typical dishwasher may have a nominal power of 2400 W based on the datasheets from manufacturers it should only consume around 780 Wh during one cleaning cycle. This corresponds to 520 W of actually used power over 1.5 hours. Furthermore, because in most cases the dishwasher is not turned on more than twice a day (typically after lunch and after dinner), the coefficient of utilization is assumed at the level of 0.25 (2 x 1.5 hours / 12 hours of daytime).

The AC appliances listed in Table 9 correspond to a typical house with 120 – 150 m2 of usable floor area where the heating is provided by a gas burner and most of the household appliances are run on a single-phase electrical circuit. It is by no means an exhaustive list of possible appliances but it serves as a good representative of a typical small urban household.

TABLE 9: List of typical AC appliances installed in a low consumption house, their installed power and coefficients of utilization [source: author's own market survey and calculations]

AC appliances	Qty.	Unit installed power (W)	Total installed power (W)	Daytime ß	Night-time ß
Lighting (energy efficient)	10	17	170	0,20	0,10
Fridge with freezer	1	18	18	1,00	1,00
Kettle	1	2200	2200	0,04	0,01
Microwave oven	1	900	900	0,05	0,02
Dishwasher	1	520	520	0,25	0,02
Washing machine	1	2200	2200	0,07	0,02
Vacuum cleaner	1	1800	1800	0,01	0,00
TV set	2	30	60	0,40	0,05
Radio	1	40	40	0,40	0,00
PC and network devices	1	110	110	0,60	0,20
Heating (water pump)	2	90	180	0,50	0,50
Electronic security system	1	50	50	1,00	1,00
Total	23	7975	8248		

Furthermore, when we multiply the installed power of each AC appliance by its respective coefficient of utilization we will get the actual power needed for this appliance in any moment during a given time period. The results of this multiplication are listed in Table 10.

TABLE 10: Calculation of actual daytime and night-time power consumption for a low consumption house [source: author’s own calculations]

AC appliances	Actual daytime consumption (W)	Actual night-time consumption (W)
Lighting (energy efficient)	34	17
Fridge with freezer	18	18
Kettle	88	22

Microwave oven	45	18
Dishwasher	130	10,4
Washing machine	154	44
Vacuum cleaner	18	0
TV set	24	3
Radio	16	0
PC and network devices	66	22
Heating (water pump)	90	90
Electronic security system	50	50
Total	733	294,4

We can see that during daytime hours the household needs on average 719 W of power and during night-time hours only 294.4 W of power. Based on these results we can proceed to perform the battery storage dimensioning whereby it is required that 294.4 W be backed up over a time period of 10 hours (i.e. during 21.00 – 7.00 time period), which corresponds to the parameter C10 of battery charging capacity. This requires 2944.0 Wh of storage capacity, which turns into 5352,73 Wh after accounting for a desired DoD of 60% and 5% losses associated with discharging of the battery (due to the XW inverter efficiency). The storage capacity of 5352.73 Wh divided by 48 V of nominal battery voltage means that a battery with at least 111.52 Ah of charging capacity is required to power the night-time consumption.

4.1.2.2 High consumption house

The estimate of AC load profile in case of a high consumption house is based on the following assumptions:

1. The house has 400 m2 of usable floor area and the annual heating demand is assumed at 60 kWh/m2.
2. All household appliances are powered by electricity - including heating and cooking.
3. Cooking is done on an induction cooking plate.
4. Heating is secured by a heat-pump based on air – water circulation.
5. In the summer 3 pcs. of conventional Air Conditioning (AC) units are used to cool down rooms.
6. The house has a more demanding electronic security system (2 cameras and 1 recording device is used additionally).

A complete list of AC appliances together with their coefficients of utilization is shown in Table 11 below.

TABLE 11: List of typical AC appliances installed in a high consumption house, their installed power and coefficients of utilization [source: author's own market survey and calculations]

AC appliances	Qty.	Unit installed power (W)	Total installed power (W)	Daytime ß	Night-time ß
Lighting (energy efficient)	20	17	340	0,30	0,10
Fridge with freezer	2	18	36	1,00	1,00
Kettle	1	2200	2200	0,04	0,02
Microwave oven	1	900	900	0,05	0,02
Dishwasher	1	520	520	0,25	0,02
Washing machine	1	2200	2200	0,07	0,02
Vacuum cleaner	1	1800	1800	0,01	0,00
TV set	2	30	60	0,40	0,05
Radio	1	40	40	0,40	0,05
PC and network devices	2	110	220	0,60	0,30
Heating (water pumps)	4	90	360	0,50	0,50
Electronic security system	1	200	200	1,00	1,00
Induction cooking plate	1	4000	4000	0,20	0,00
Air-conditioning units[18]	3	2200	6600	0,05	0,05
Heat-pump (air-water)[19]	1	2300	2300	1,00	1,00
Total	42	14325	19476		

Again, by multiplying the total installed power of an AC appliance with the corresponding ß we can estimate the actual average daytime and night-time power consumption (Table 12). However, in this case we also have to take into consideration the seasonal character of operation of heat-pump and air-conditioning units – the two major consumers of energy. In fact, a typical season for heat-pump usage in the climate conditions of Bratislava, Slovakia is October - March (i.e. cca 180 days) whereas air-conditioning units are mostly used in June, July and August (i.e. cca 90 days).

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[18] The coefficients of utilization are calculated from the estimate of yearly energy consumption of 245 kWh/year/AC unit of Toshiba Super Daiseikai 6 inverter unit, the specifications were downloaded from http://www.toshiba-klima.at/produkte/heimbereich_singlesysteme.php?modell=16

[19] this is based on the parameters obtained from the simulation of Daikin Altherma 16 kW (heat) split type unit, the simulation was performed in Daikin Altherma simulator downloaded from http://www.daikinaltherma.sk/

TABLE 12: Calculation of actual daytime and night-time power consumption for a high consumption house [source: author's own calculations]

AC appliances	Actual daytime consumption (W)	Actual night-time consumption (W)
Lighting (energy efficient)	102	34
Fridge with freezer	36	36
Kettle	88	44
Microwave oven	45	18
Dishwasher	130	10,4
Washing machine	154	44
Vacuum cleaner	18	0
TV set	24	3
Radio	16	2
PC and network devices	132	66
Heating (circ. pumps)	180	180
Electronic security system	200	200
Induction cooking plate	200	0
Air-conditioning	340	340
Heat-pump (air-water)	2300	2300
Total consumption	3955	3267,4
Total consumption during summer	1665	977,4
Total consumption during winter	3635	2947,4

We can see that during daytime hours in the summer the household needs on average 1655 W of power while during night-time hours only 977.4 W of power are needed. However, due to the heat-pump operation during the winter the household needs on average 3625 W of power while during night-time hours it demands 2937.4 W of power. In this case the dimensioning of a battery storage system presents us with a dilemma. If we were to back up 2937.4 of winter night-time consumption over 10 hours with DoD of 60 % and 5% losses associated with discharging (due to the XW inverter efficiency) it would require 53,41 kWh of storage capacity, which means charging capacity of 1112.7 Ah per battery cell. Because this size of battery system is extremely costly it is necessary to decide which AC loads are of primary importance – meaning that these loads must be powered at all times - and which will act as defferable loads – meaning that they will be powered only when all the primary AC loads have been covered. In this case, due to its high power consumption, it is clearly convenient to set the heat-pump as a defferable AC load while all other loads can be set as primary. Consequently, if the summer night-time consumption is used for dimensioning of the battery system based on the above-mentioned calculation we will need at least 17.77 kWh or 370.2 Ah of charging capacity per battery cell.

4.1.3 Feed-in tariff support conditions

In this section we will proceed to describe the FiT support conditions in the selected location of the hybrid PV system - that is in Slovakia. Because in the sensitivity analysis we will be changing the level of FiT, it is not so important which country's support system was selected as long as it's based on a FiT mechanism. However, for reasons mentioned further in this section Slovakia can be considered a representative of certain type of support conditions for roof PV systems. Actually, this kind of support scheme is also valid in the Czech Republic.

In 2009 the Slovak parliament passed the Act on the Promotion of Renewable Energy Sources (Act No. 309/2009 Coll.) which is based to a large extent on the principles set in the German Erneuerbare-Energien-Gesetz (EEG). According to the law, the FiTs are fixed for a guaranteed period of 15 years from the date when the RES was put into operation. Also, the FiT mechanism is based on a 'green bonus' calculation, which practically means that FiTs are compounds of a price for electricity to cover grid losses (roughly corresponds to the base-load market price of electricity) and a special supplementary charge that changes once a year when a new reference price for electricity to cover grid losses is set by the energy regulation office. The supplementary charge is received for every kWh produced in a RES which is approved by the regulation office and it doesn't even have to be connected to the grid. On the other hand, the base-load market price of electricity is received only when the electricity from a RES is delivered to the grid. Hence, from the legislative point of view it is possible to distinguish between two types of PV system operation:

1. PV system produces energy which is consumed directly by household appliances. In this case the owner of the PV system obtains two benefits: 1) She receives a supplementary charge multiplied by the amount of produced and self-consumed energy, and 2) she doesn't have to purchase the self-produced amount of electricity from the grid. Both of these benefits increase her household cash flow.
2. PV system produces surplus energy which is delivered to the grid because of low household self-consumption (especially in summer). In this case the owner of the PV system receives a full FiT for the surplus energy delivered to the grid but she doesn't have any additional benefit from a lower self-consumption.

According to the latest decree of the energy regulatory office, the current FiT for roof PV systems is 194.54 EUR/MWh that is valid for <100 kWp systems. From this tariff the price for electricity to cover grid losses amounts to 60.1 EUR/MWh, which means that the supplementary charge is 134.44 EUR/MWh. However, in May 2012 the energy regulation office proposed a fairly big reduction in this FiT, which is to come into force starting from July 1, 2012. The new FiT shall be set to 119.11 EUR/MWh from which the price for electricity to cover grid losses would still amount to 60.1 EUR/MWh but the supplementary charge would decrease to 59.01 EUR/MWh. Because the new FiT is not enacted yet in the simulation of energy yield we will calculate with the currently valid FiT as the basic assumption.

4.1.4 Commercial price of electricity

In this section we will present how the commercial price of electricity (CPE) for household owners is structured, the current market rates as well as historical developments and likely trends for the future. The CPE is one of the three key driving factors behind the hybrid PV system economics. In general, the CPE is a compound of several various components which are derived from the process of electricity generation, the transmission and distribution and the regulation of the electricity market by the state.

To provide a better overview of the individual components and their influence on the CPE we will now proceed to analyze the structure of the CPE directly at our consumption place located in Bratislava, Slovakia where it is possible to distinguish the following components:

1. Base-load price of electricity. Due to the liberalization of electricity markets in the EU, which has led to a complete unbundling of electricity generation from distribution and trading, this component is invariably a result of a competitive market trading of electricity as a commodity.
2. Distribution & transmission. This component reflects the costs of the grid operator associated with the delivery of electricity to the final point of usage.
3. Grid losses. The end user has to pay for losses in the grid (in electricity lines, transformers and substations) associated with transmission & distribution of electricity to the final point of usage.
4. System services. These are costs of operation of the transmission grid associated with balancing of electricity consumption and production.
5. System operation. This component includes mainly the support of electricity from RES and also from coal-based power plants. Due to the increased RES

promotion in the recent years the portion of this component (in %) has also been increasing.

6. Nuclear fund. Slovakia currently operates two nuclear power plants, of which one has already phased out one of its blocks. The nuclear fund component was introduced to cover the costs of nuclear power plants and waste disposal.
7. Excise tax. All electricity in Slovakia, except when it was produced in RES, is subject to an excise tax. This component depends on legislative which must be passed by the parliament.
8. Value added tax (VAT). Like all products and services electricity is also subject to VAT which is currently set to 20%.

The actual rates of the above-mentioned CPE components depend either on the parliament (points 7 & 8), the energy regulation office (points 2 - 6) or the market (point 1). Their current rates for small household owners in Slovakia are listed in Table 12. The rate for base-load price is provided as an average of prices offered by all energy traders and corresponds to a standard single tariff product.

TABLE 13: Structure of CPE rates [source: ZSE Energia[20], Elektricka energia[21]]

CPE components	Rates (EUR/kWh)
Base-load price	0,06235
Distribution & transmission	0,012668
Grid losses	0,01183
System services	0,00733
System operation	0,0157
Nuclear fund	0,003
Excise tax	0,00132
Value added tax	20%
Total	0,1370376

We can see that the base-load price makes less than 50% of CPE. All the rest can be attributed to factors which are not based on market conditions but are a result of energy sector regulation.

Furthermore, for the purposes of feasibility analysis it is not sufficient to know the current CPE for household owners but we also need to make an educated assumption about the probable future development of CPE. To achieve this it is

[20] http://www.zse.sk/index.php?www=sp_file&id_item=868

[21] http://www.elektrickaenergia.sk/ceny-domacnosti-tabulka.php

instrumental to look at the historical development of CPE in Slovakia. According to official data available at the Eurostat Energy database[22] for half-years during the period of 2004 – 2011, there has been a clear rising trend in the CPE for retail consumers (Figure 5) in Slovakia. As a matter of fact, in this time period the average CPE has increased by 36.2%. For comparison Figure 5 also shows the historical development of CPE for industrial consumers. We can see that it demonstrates a much stronger rising trend than CPE for retail consumers.

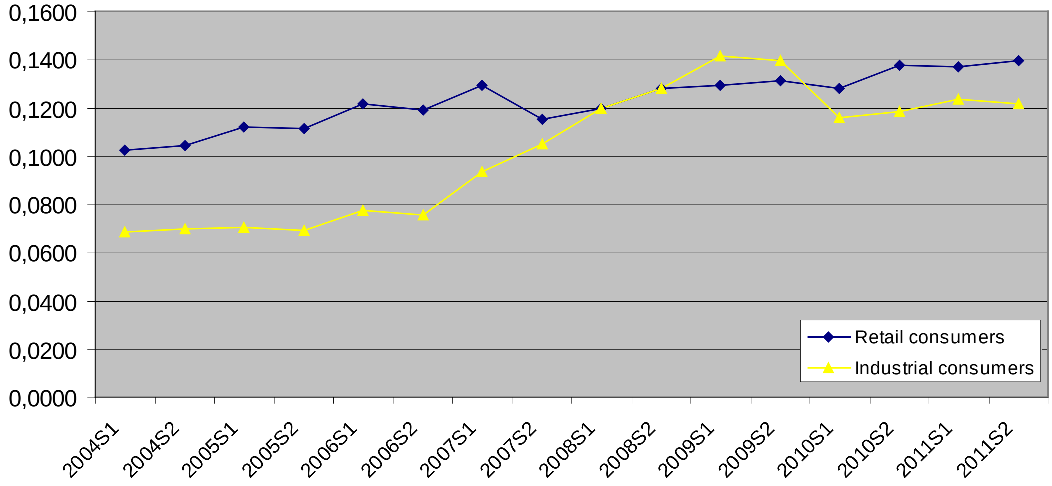

FIGURE 4: Historical development of CPE (Y-axis, denoted in EUR/kWh) for retail and industrial consumers in the period of 2004 – 2011 (X-axis) [source: Eurostat]

From the available data we can also calculate annual compounded growth rate (CAGR) of CPE over the given time period. However, before we do this we should take into account the fact that the methodology of CPE calculation changed in 2007, which means that data for the second half of 2007 onwards are likely to spoil the whole dataset. To overcome this obstacle we will have to calculate CAGR separately for the periods of 2004S1 – 2007S1 and 2007S2 – 2011S2. CAGR for the former period was calculated at 6.75% while for the latter period the rate is 4.3%. In comparison, during the same periods the CAGR of CPE for industrial consumers was 9.08% and 3.37% respectively.

Based on the above-mentioned analysis of historical CPE development trends, we can assume that the CPE will continue to grow in Slovakia even in the future. The exact extent of growth is always debatable but it seems to be rational to assume a growth rate of at least 3% p.a. This assumption reflects a conservative view of the

[22] http://epp.eurostat.ec.europa.eu/portal/page/portal/energy/data/database

potential for future CPE growth and is consistent with the fact that as of July 2011 the Slovak energy regulator stopped supporting large-scale PV installations, which were arguably the main driver of the relatively large Y/Y increases in the 'system operation' component of CPE.

4.1.5 Investment costs

In chapter 3 of this work we developed the hybrid PV system functional design and we also described the technical parameters of the main technological components selected for the PV system as well as the concept of their wiring. Based on this technological design, we will now make a list of costs for each of the components as well as for their mounting, electrical installation and other ancillary works. Tables 14 and 15 provide a comprehensive breakdown of the investment costs for the single-phase as well as three-phase PV system.

TABLE 14: Breakdown of investment costs of single-phase hybrid PV system with installed power of 5 kWp (DC)

Item	Tech. specification	Qty.	Unit costs (EUR/unit)	Total costs (EUR)	Total costs/Wp
PV modules	Canadian Solar 250 Wp multicrystalline	20,0	150,0	3 000,0	0,60
Roof mounting system	Hilti MSP with inclination of 35°	1,0	650,0	650,0	0,13
Solar charger/MPP tracker	XW MPPT 80 600 with external battery sensor	1,0	764,6	764,6	0,15
Hybrid inverter	XW4548-230-50 with controller, 4,5 kW AC output	1,0	1 611,5	1 611,5	0,32
String box	Contains fuse cases for 4 string (+ and -) DC cables, 4 x 10 A DC fuses for 800 V	1,0	120,0	120,0	0,02
DC/AC cabling	6 mm2 DC cables for strings, 25 mm2 DC cables for connecting solar charger with batteries and inverter	1,0	900,0	900,0	0,18
Battery storage system	VLA type, 12V 3 OPzS solar.power 200, 151.0 Ah at C10, made by Hoppecke	4,0	402,9	1 611,6	0,32
Grid connection & metering	Box with disconnector & single-phase meter	1,0	600,0	600,0	0,12
Installation works	Installation of all system parts & materials, functional tests	1,0	350,0	350,0	0,07
System design	Realization design for a particular house	1,0	300,0	300,0	0,06
Total costs				9 907,69	1,98

TABLE 15: Breakdown of investment costs of three-phase hybrid PV system with installed power of 18 kWp (DC)

Item	Tech. specification	Qty.	Unit costs (EUR/unit)	Total costs (EUR)	Total costs/Wp

PV modules	Canadian Solar 250 Wp multicrystalline	72,0	145,0	10 440,0	0,58
Roof mounting system	Hilti MSP with inclination of 35°	1,0	2 340,0	2 340,0	0,13
Solar charger/MPP tracker	XW MPPT 80 600 with external battery sensor	3,0	764,6	2 293,7	0,13
Hybrid inverter	XW6048-230-50 with controller, 6 kW AC output	3,0	1 656,0	4 968,0	0,28
String box	Contains fuse cases for 4 string (+ and -) DC cables, 4 x 10 A DC fuses at 900 V	3,0	120,0	360,0	0,02
DC/AC cabling	6 mm2 DC cables for strings, 25 mm2 DC cables for connecting solar charger with batteries and inverter	1,0	3 240,0	3 240,0	0,18
Battery storage system	VLA type, 48V, 5 OPzS solar.power 520, made by Hoppecke, 390.0 Ah at C10	24,0	154,9	3 717,4	0,21
Grid connection & metering	Box with surge guards, digital protection and disconnector	1,0	1 500,0	1 500,0	0,08
Installation works	Installation of all system parts & materials, functional tests	1,0	1 260,0	1 260,0	0,07
System design	Realization design for a particular house	1,0	400,0	400,0	0,02
Total costs				30 519,01	1,70

The prices of the technological components listed in Table 14 and 15 are based on actual price offers received directly from the manufacturers or suppliers of these devices. Other items, such as DC/AC cabling, installation works and grid connection & metering, are priced up based on the author's own experience with roof PV installations and a market survey of comparable works. We can see that the cost / Wp of the three-phase PV system is almost 15% lower compared to the single-phase PV system. This is firstly because by enlarging the system not all the components scale up proportionately (e.g. grid connection & metering, system design). Secondly, there is economy of scale in play, which is mostly visibly in case of PV modules, hybrid inverters and battery storage.

Regarding the height of total investment costs, we should also take into account the date when these hybrid PV systems are planned to be realized. The reason for this consideration is the ongoing turbulence on the PV market, which started around 2010 when the prices of PV modules started to fall among strong emerging competition from Chinese manufacturers. Given the recent developments on the PV markets it is highly rational to expect further decreases mainly in the PV module prices[23]. Another item that is likely to undergo some price reductions is the battery

[23] this is consistent with price declines already occurred in 2012 and documented e.g. at http://www.solarserver.com/service/pvx-spot-market-price-index-solar-pv-modules.html, the assumption is also supported by the predictions of NPD Solarbuzz about incoming price falls

storage system where there is space for further technological improvements with a positive impact on the EUR/kWh price.

4.1.6 Operation & maintenance costs

Although the hybrid PV system is designed to operate automatically, there are still some costs associated with its operation & maintenance. Table 16 and 17 shows the O&M cost breakdown for the single-phase and for the three-phase PV system. We can realistically assume that even though the three-phase PV system is more than 3 times larger it will not cost more than 3 times more to maintain it.

TABLE 16: Breakdown of O&M costs for single-phase hybrid PV system

Item	Description	Unit costs (EUR/unit)	Annual costs (EUR)	Annual adjustment for inflation (% p.a.)
PV system (all parts)	Periodic technical inspection performed once per year to prevent incipient failures	80,0	80,0	3,00%
Battery storage system	Periodic watering performed 4 times per year to ensure sufficient level of electrolyte	25,0	100,0	3,00%
Electrical revisions	Mandatory revisions of low voltage electrical installations - must be performed at least once per 5 years	100,0	20,0	3,00%
Total			200,0	3,00%

TABLE 17: Breakdown of O&M costs for three-phase hybrid PV system

Item	Description	Unit costs (EUR/unit)	Annual costs (EUR)	Annual adjustment for inflation (% p.a.)
PV system (all parts)	Periodic technical inspection performed once per year to prevent incipient failures	80,0	80,0	3,00%
Battery storage system	Periodic watering performed 4 times per year to ensure sufficient level of electrolyte	75,0	300,0	3,00%
Electrical revisions	Mandatory revisions of low voltage electrical installations - must be performed at least once per 5 years	100,0	20,0	3,00%
Total			400,0	3,00%

in 2012 published at http://www.pv-tech.org/news/npd_solarbuzz_solar_module_prices_to_fall_at_least_29_in_2012_as_market_dec

4.2 System simulation

4.2.1 System simulation in HOMER Legacy

Utilizing the electrical parameters of all the technical and technological components described in chapter 3 of this work, we will now perform a system simulation in HOMER Legacy program. The following inputs were defined in the program settings:

- GPS coordinates and average daily radiation data were copied into the “Solar resources” tab
- Average daily temperature conditions were copied into the corresponding fields in the “Temperature” tab
- In the “Equipment to consider” section Primary Load, PV, Converter and Battery components blanks were checked
- In the “Primary Load Inputs” tab the assumed AC load profiles were defined
- In the “Converter Inputs” tab efficiency of both XW charger and XW inverter were defined in the “Efficiency (%)” blank. The overall efficiency was calculated as 96% x 95.6% = 91.78 %.
- In the “Battery Inputs” tab Hoppecke 4 OPzS 200 battery type was selected for the single-phase PV system simulation and Hoppecke 6 OPzS 600 battery type for the three-phase PV system simulation. In the “Advanced” section of this tab the number 24 was defined to obtain a 24 x 2V = 48V bus.
- In the “PV Inputs” the following inputs were defined: Lifetime 25 years, Derating factor 90%[24], Slope 34 degrees, Azimuth 0 degrees, Ground reflectance 20%, Temp. coefficient of power -0.43%/C, Nominal operating temperature 45°C, Efficiency at STC 15.53%
- In the “Constraints” tab Maximum annual capacity shortage was defined as 50%[25], Operating reserve as 10%, Annual peak load as 0%

Based on the above-mentioned inputs two simulations were performed for the single-phase and three-phase PV system respectively. The outputs from the simulations are included in Annex A and Annex B of this work.

As we can see, in case of the single-phase hybrid PV system the PV array is estimated to produce 6,053 kWh/yr, of which 3,674 kWh are consumed by the AC loads. This amount includes day-time consumption directly from the PV array as well

[24] corresponds to system losses of 10% represented by temperature, module quality, array soiling, module array mismatch, irradiance level and wiring losses

[25] we don’t try to cover all the AC consumption by PV power

as night-time consumption from the battery storage. It also means that the PV system is capable of supplying 71.4% of the total annual energy demand of the house. However, the PV system also generates 1,821 kWh of energy which cannot be utilized neither by the AC loads nor in the battery storage, and is thus sold to the grid as energy surplus. Therefore, on the whole the PV system generates 5,495 kWh of valuable electricity, which is either used to generate savings from otherwise necessary grid purchases or it is sold to the grid as a surplus and paid with FiT.

In case of the three-phase hybrid PV system the picture is slightly different. The PV array is expected to generate 20,335 kWh/yr of useful energy from which 9,984 kWh will be consumed by AC loads and 10,351 kWh will be sold to the grid. However, we can also see that there is a considerable amount of unmet electric load due to the energy demanding operation of the heat pump. Overall the PV system is capable of supplying of only 51.0% of the total annual energy demand of the house.

4.2.2 System simulation in PVSYST

For a system simulation in PVSYST we will use the stand-alone project design mode. To perform the simulation the program needs to have defined namely the meteorological data, geometrical orientation of the PV array, user's needs (AC load) and the technical parameters of the main system components (i.e. batteries, PV modules and charger/converter). The program actually requires detailed technical parameters of the system components that can either be loaded from the program's components database or they can be customized as new components. Moreover, the system section also supports an in-depth calculation of array losses.

Using the same configuration of inputs as for HOMER Legacy program we are able to perform the system simulation for the single-phase PV system. The report from the simulation is included in Annex C of this work. According to the results, the PV array is expected to produce 5667 kWh of energy per year of which 5182 kWh is the available energy AC output. The difference accounts for losses in the MPPT charger and the hybrid inverter. Furthermore, we can see that 44.3 % or 2,295.6 kWh from the AC output energy will be supplied to the user directly from the PV array production and 3,755 kWh in total will be supplied to the user from the PV array and battery together. Hence, by subtracting we can calculate that 1459.4 kWh will be provided by the battery storage. The excess electricity which cannot be consumed by AC loads directly or from the battery storage amounts to 1427 kWh. If we calculate the fraction of the annual energy demand covered by the PV system energy yield we can conclude that the PV system will supply 72.5%.

Unfortunately in PVSYST it is impossible to perform the same kind of simulation for the three-phase PV system because the actual version of the program supports a system configuration with only one charger/converter. This is a rather inconvenient drawback of the program and we can only hope that it will be resolved in later versions.

4.2.3 Summary of simulation results

When we compare the results from the simulations in HOMER Legacy and PVSYST we can see that in case of the single-phase PV system they produced results that are not too far away from each other in magnitude. However, we will prefer the results from the PVSYST for the following reasons:

1. Most of the inputs can be defined in a more detailed and therefore more precise way.
2. The simulation takes into account specific technical parameters of each of the devices whereas in case of HOMER Legacy the converter and the PV modules have only basic properties available.

In case of the three-phase PV system, as the simulation in PVSYST couldn't be performed we will have to use the results of the simulation in HOMER Legacy.

4.3 Economic valuation model

In this section we construct an economic model which ultimately reveals the critical feasibility parameters based on which we can valuate both of the developed hybrid PV systems. By utilizing the results from the previous chapters of this work we can establish a baseline scenario of economic feasibility. This scenario can then be a basis for the subsequent sensitivity analysis.

In principle, an economic model is a future cash flow projection of the investment for the time period of its technical or economical life (whichever is more appropriate in given case). In this case we will make a cash flow projection for 15 years because this is the FiT guaranteed time in Slovakia. Furthermore, we will make the following assumptions about the model inputs:

- CPE will increase by 3% p.a.
- The efficiency of the installed PV modules will decrease by 0.5% p.a.

- O&M costs will increase by 3% p.a. (in line with CPE)
- Maintenance CAPEX is assumed at the level of costs of battery storage in the 8th year of operation (the end of its cycle life-time) and at the level of costs of hybrid inverters in the 10th year of operation
- Tax rate on profits from the sale of electricity and green bonus is 19% (currently valid flat tax rate in Slovakia)
- VAT on solar products is 20% (currently valid rate in Slovakia)
- Depreciation of investment costs is linear, the period for solar technologies is 6 years
- Discount rate on equity is 5% p.a. – this is arbitrarily chosen and reflects the alternative costs of money invested in commissioning of the PV systems
- AC loads remain constant during the entire time period

The economic models for the single-phase and three-phase PV system are included in Annex D and Annex E respectively.

The single-phase PV system's baseline scenario obviously cannot pass the test of economic feasibility as it shows highly negative results. The IRR is calculated at 1.13% (< 5% discount rate), the NPV of equity is negative at -2,777 EUR, the simple payback time is 14.17 years and the discounted payback time is much longer than 15 years. On the other hand, the baseline scenario for the three-phase PV system is proved to be economically feasible with respect to our assumptions. We can see that the IRR is 6.10% (> 5 % discount rate), the NPV of equity is positive at 2,670 EUR, the simple payback time is 10.57 years and the discounted payback time is 13.76 years. However, due to its relatively long payback time and low IRR it still cannot be considered an overly attractive investment.

One important point we have to make about the economic model is that it calculates with costs which include a relatively high VAT that is currently valid in Slovakia. However, there are ways to overcome these additional investment costs. They will be discussed in the next chapter.

4.4 Sensitivity analysis

It is important to take into account the fact that some economic factors with a significant influence to the economic feasibility tend to change rather quickly. We will call these key economic factors and they include namely the feed-in-tariff support, grid electricity prices and investment costs of the PV system. The aim of the sensitivity analysis is to evaluate the effects that any changes in these parameters might have on the overall economic feasibility of the PV systems. Ultimately we will be trying to locate a breakeven point in which the investment starts to be economically feasible.

As to the method of performing sensitivity analysis, we will be changing the input parameters of one key economic factor while all other factors remain constant. In this process the following 4 scenarios will be utilized:

Scenario 1: Decrease in the value by 10%

Scenario 2: Increase in the value by 10%

Scenario 3: Breakeven point value – will be located by goal seek function

Scenario 4: Value of special interest – will be used in case of FiT support conditions as "no green bonus" scenario and in case of investment costs as "no VAT" scenario

We will then measure the sensitivity of overall economic performance to the changes in the input parameters according to the above-mentioned scenarios. The results from the sensitivity analysis are summarized in Annex F for the single-phase PV system and in Annex G for the three-phase PV system. We can summarize the results revealed in the sensitivity analysis in the following way:

1. Both of the systems are sensitive to the changes in the key economic factors in the following order of magnitude: 1) investment costs, 2) FiT support conditions, 3) CPE.
2. For both of the systems changes in all of the key economic factors have the biggest impact on the NPV indicator.
3. All of the economic indicators are extremely sensitive to changes in investment costs
4. For the single-phase PV system the breakeven point values are substantially far away from the baseline scenario values.
5. For the single-phase PV system even the "no VAT" scenario doesn't produce economic feasibility.
6. In case of the three-phase PV system the discounted payback time (DTP) indicator has much a smaller sensitivity to the changes in FiT support conditions and CPE than to the changes in investment costs.
7. None of the PV systems can be economically feasible under the "no green bonus" scenario.

5 Summary of results

This section will hereby provide a concise summary of the results obtained from the technical and the economic part of this work. In the technical part of this work we developed a single-phase and a three-phase hybrid PV system based on commercially available products manufactured by Schneider Electric, Inc. All the most important results from the economic feasibility analysis are comprehensively summarized in Table 18 below.

TABLE 18: Summary of results of the economic feasibility analysis

Indicator	Single-phase PV (5 kWp)	Three-phase PV (18 kWp)
System Energy Yield (kWh)	5 182	20 335
Energy Self-consumed (kWh / % of System Energy Yield)	3 755 / 72.5%	9 984 / 49.1%
Energy Sold into the Grid (kWh / % of System Energy Yield)	1 427 / 27.5%	10 351 / 50.9%
Investment costs (EUR)	11 889	36 623
IRR (% p.a.)	1,13%	6,10%
NPV (EUR)	-2 777	2 670
DPT (years)	> 20	13,76

The single-phase PV system is most suitable for a low consumption house with single-phase AC loads. In the assumed conditions this kind of hybrid PV system is capable of supplying 72.5% of the annual energy demand. However, due to its relatively small size (5 kWp at STC) and the associated low potential for creating economy of scale it suffers from much higher costs / Wp and is ultimately not economically feasible under the assumed economic valuation criteria. The economic feasibility of this PV system can be achieved either by a 27.4% increase in the FiT tariff (i.e. 0.24775 EUR/kWh) or a 44.5% increase in the CPE (i.e. 0.1980 EUR/kWh), or a 23.4% decrease in its investment costs (9,113 EUR).

The three-phase PV system is developed specifically for high consumption houses which have several three-phase AC loads with high installed power. Because the system’s power generation curve fails to copy the house’s AC consumption profile there is a much larger amount of surplus energy. In fact the PV system can only supply 50.9% of annual energy demand of AC loads whereas the remaining 49.1% is sold to the grid at FiT. However, due to its larger size the PV system is able to draw benefits from economy of scale and some quantitative discounts, which leads to lower costs / Wp. This is the main reason why the three-phase PV system can be economically feasible even under the baseline scenario. Nevertheless, its economic performance is far from being called lucrative and the PV system couldn't be feasible without a FiT of at least 0.16893 EUR/kWh. On the other hand, should the investor manage to avoid paying VAT on the investment costs of the system components, the economic valuation could result in an IRR of 9.19%, NPV of 8,773 EUR and DTP of 11.04 yrs.

6 Conclusions

In this work we have successfully managed to develop single-phase and three-phase configurations of a unique hybrid PV system which meets all the required functions defined in the initial assignment. We have showed that by using deep-cycle battery storage the hybrid PV system effectively increases the ratio of energy consumed by house's own AC loads. This shows us a clear pathway towards achieving higher energy autonomy for the home owner.

Moreover, because the PV system is designed to be in grid-on operation all the energy surpluses can be fed to the grid and sold for a feed-in-tariff. This way the PV system is capable of generating a high portion of valuable energy either in terms of electricity bill savings or revenues from electricity sale. In fact, after having performed an economic feasibility analysis we can see that the three-phase PV system is already feasible even in the baseline scenario. On the other hand, the single-phase PV system is still too costly to achieve a desired level of economic performance.

By conducting a sensitivity analysis with respect to selected key economic factors we have managed to identify not just the breakeven levels for achieving economic feasibility but also several possible areas for its further improvement. The most important area, which also has the greatest effect on the economic feasibility, is further lowering of the investment costs, for instance in the battery storage segment.

On the whole, we can conclude that the developed hybrid PV system, especially in its three-phase configuration, has a considerable potential of wider market deployment.

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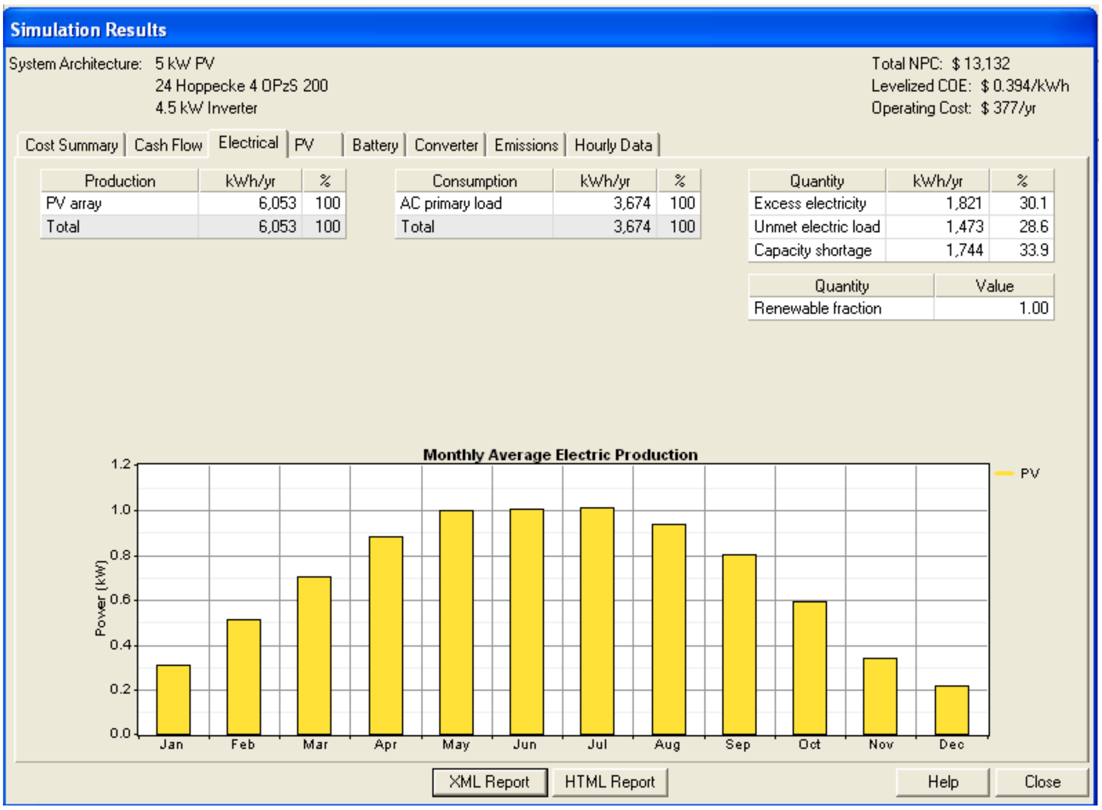
Annex A


Simulation Results
System Architecture: 5 kW PV
24 Hoppecke 4 OPzS 200
4.5 kW Inverter
Total NPC: $ 13,132
Levelized COE: $ 0.394/kWh
Operating Cost: $ 377/yr
Cost Summary | Cash Flow | Electrical | PV | Battery | Converter | Emissions | Hourly Data
Production | kWh/yr | %
PV array | 6,053 | 100
Total | 6,053 | 100
Consumption | kWh/yr | %
AC primary load | 3,674 | 100
Total | 3,674 | 100
Quantity | kWh/yr | %
Excess electricity | 1,821 | 30.1
Unmet electric load | 1,473 | 28.6
Capacity shortage | 1,744 | 33.9
Quantity | Value
Renewable fraction | 1.00
Monthly Average Electric Production
PV
Power (kW)
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1.0
0.8
0.6
0.4
0.2
0.0
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XML Report
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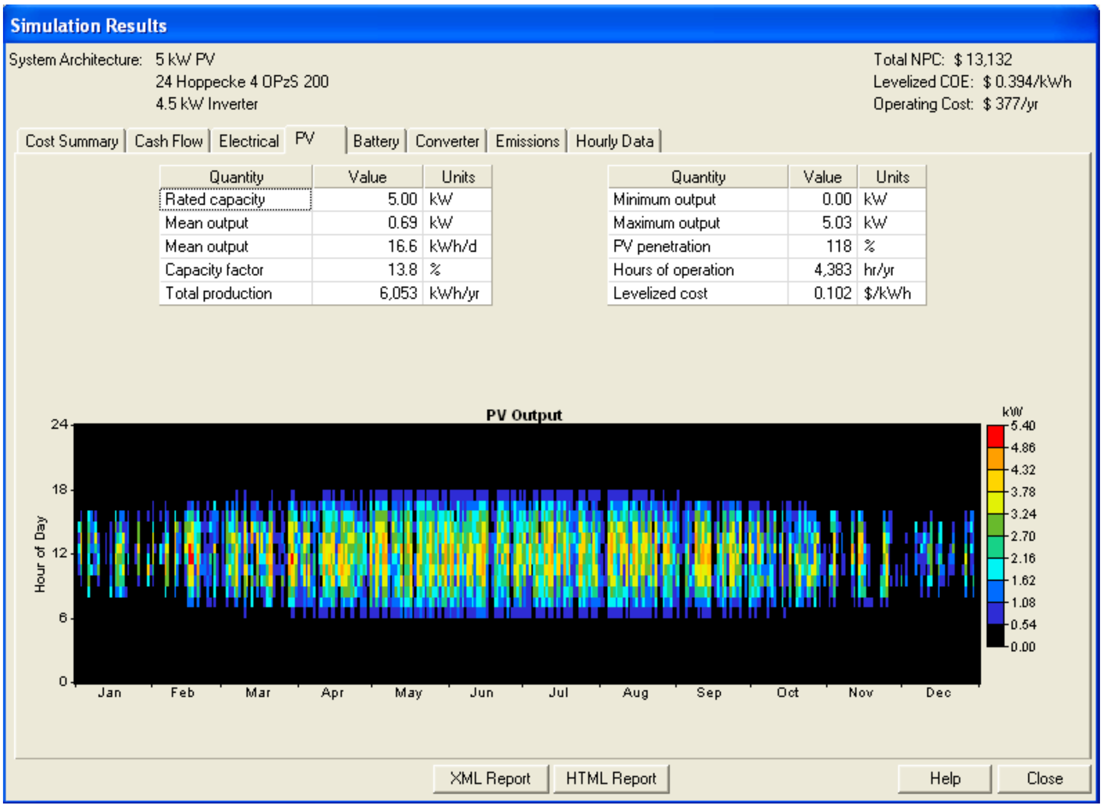
Simulation Results
System Architecture: 5 kW PV
24 Hoppecke 4 OPzS 200
4.5 kW Inverter
Total NPC: $ 13,132
Levelized COE: $ 0.394/kWh
Operating Cost: $ 377/yr
Cost Summary | Cash Flow | Electrical | PV | Battery | Converter | Emissions | Hourly Data
Quantity | Value | Units
Rated capacity | 5.00 | kW
Mean output | 0.69 | kW
Mean output | 16.6 | kWh/d
Capacity factor | 13.8 | %
Total production | 6,053 | kWh/yr
Quantity | Value | Units
Minimum output | 0.00 | kW
Maximum output | 5.03 | kW
PV penetration | 118 | %
Hours of operation | 4,383 | hr/yr
Levelized cost | 0.102 | $/kWh
PV Output
Hour of Day
24
18
12
6
0
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
kW
5.40
4.86
4.32
3.78
3.24
2.70
2.16
1.62
1.08
0.54
0.00
XML Report
HTML Report
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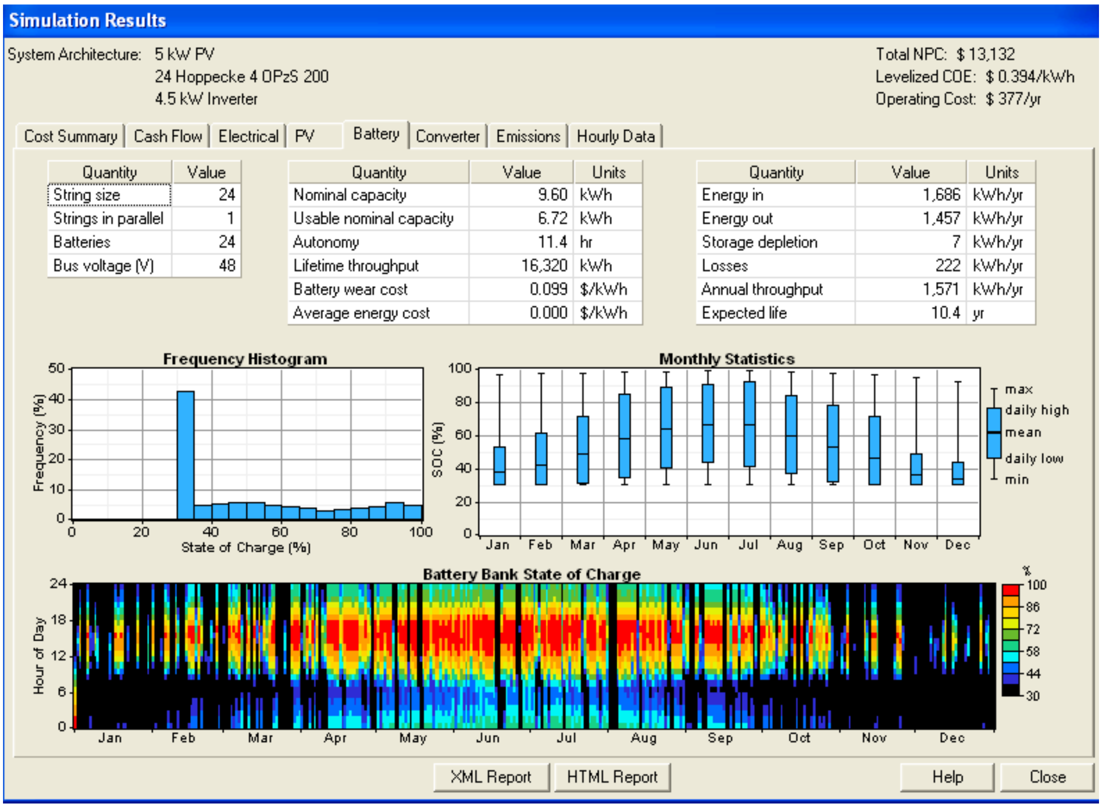


Simulation Results

System Architecture: 5 kW PV
24 Hoppecke 4 OPzS 200
4.5 kW Inverter

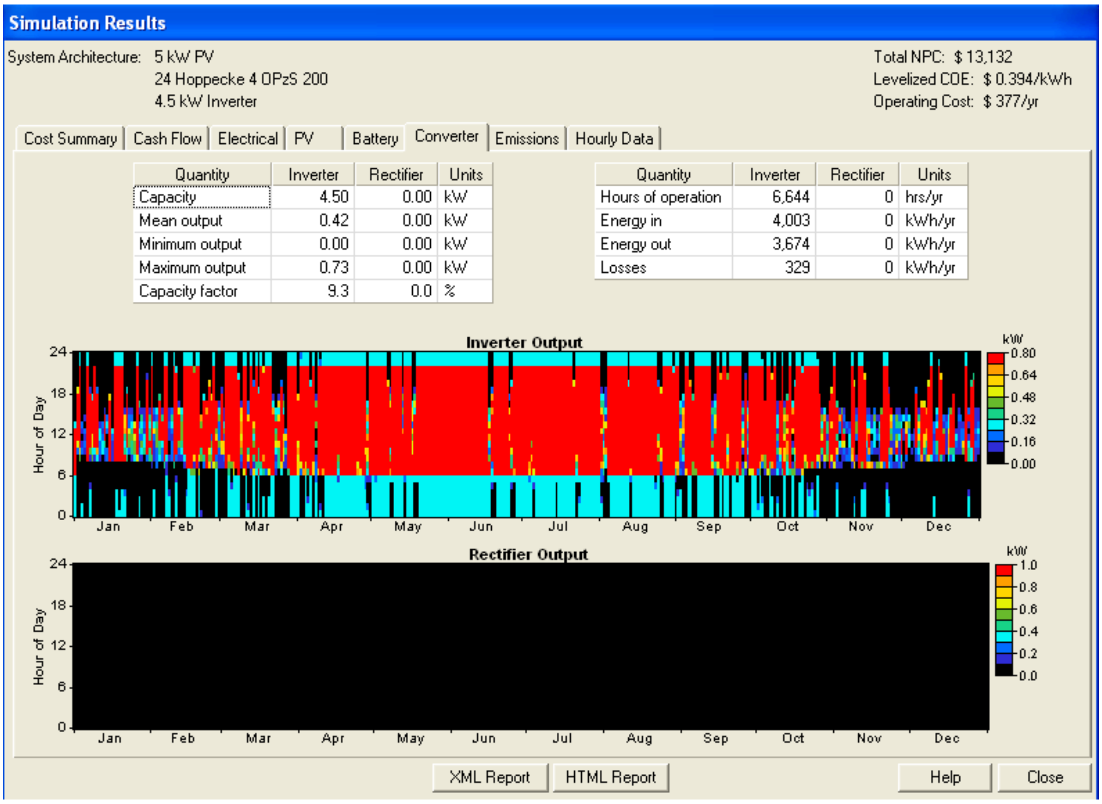
Total NPC: $ 13,132
Levelized COE: $ 0.394/kWh
Operating Cost: $ 377/yr

Cost Summary | Cash Flow | Electrical | PV | Battery | Converter | Emissions | Hourly Data

Quantity	Value
String size	24
Strings in parallel	1
Batteries	24
Bus voltage (V)	48

Quantity	Value	Units
Nominal capacity	9.60	kWh
Usable nominal capacity	6.72	kWh
Autonomy	11.4	hr
Lifetime throughput	16,320	kWh
Battery wear cost	0.099	$/kWh
Average energy cost	0.000	$/kWh

Quantity	Value	Units
Energy in	1,686	kWh/yr
Energy out	1,457	kWh/yr
Storage depletion	7	kWh/yr
Losses	222	kWh/yr
Annual throughput	1,571	kWh/yr
Expected life	10.4	yr



Simulation Results

System Architecture: 5 kW PV
24 Hoppecke 4 OPzS 200
4.5 kW Inverter

Total NPC: $ 13,132
Levelized COE: $ 0.394/kWh
Operating Cost: $ 377/yr

Cost Summary | Cash Flow | Electrical | PV | Battery | Converter | Emissions | Hourly Data

Quantity	Inverter	Rectifier	Units
Capacity	4.50	0.00	kW
Mean output	0.42	0.00	kW
Minimum output	0.00	0.00	kW
Maximum output	0.73	0.00	kW
Capacity factor	9.3	0.0	%

Quantity	Inverter	Rectifier	Units
Hours of operation	6,644	0	hrs/yr
Energy in	4,003	0	kWh/yr
Energy out	3,674	0	kWh/yr
Losses	329	0	kWh/yr

Annex B

Simulation Results

System Architecture: 18 kW PV
24 Hoppecke 6 OPzS 600
18 kW Inverter

Total NPC: $ 34,150
Levelized COE: $ 0.377/kWh
Operating Cost: $ 400/yr

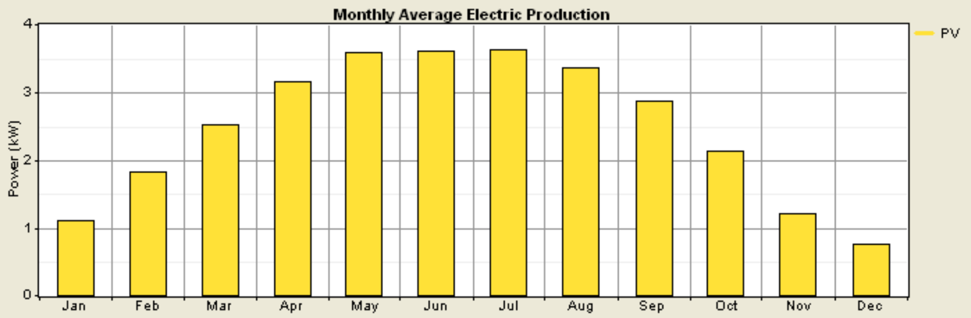
Cost Summary | Cash Flow | Electrical | PV | Battery | Converter | Emissions | Hourly Data

Production	kWh/yr	%
PV array	21,789	100
Total	21,789	100

Consumption	kWh/yr	%
AC primary load	9,984	100
Total	9,984	100

Quantity	kWh/yr	%
Excess electricity	10,351	47.5
Unmet electric load	9,579	49.0
Capacity shortage	10,988	56.2

Quantity	Value
Renewable fraction	1.00



Simulation Results

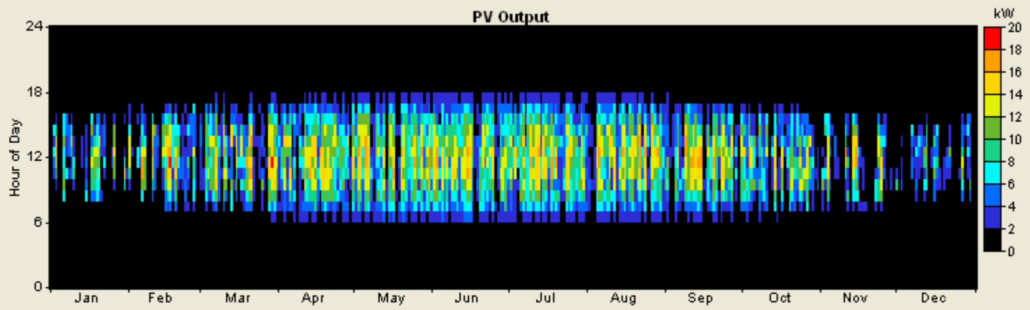
System Architecture: 18 kW PV
24 Hoppecke 6 OPzS 600
18 kW Inverter

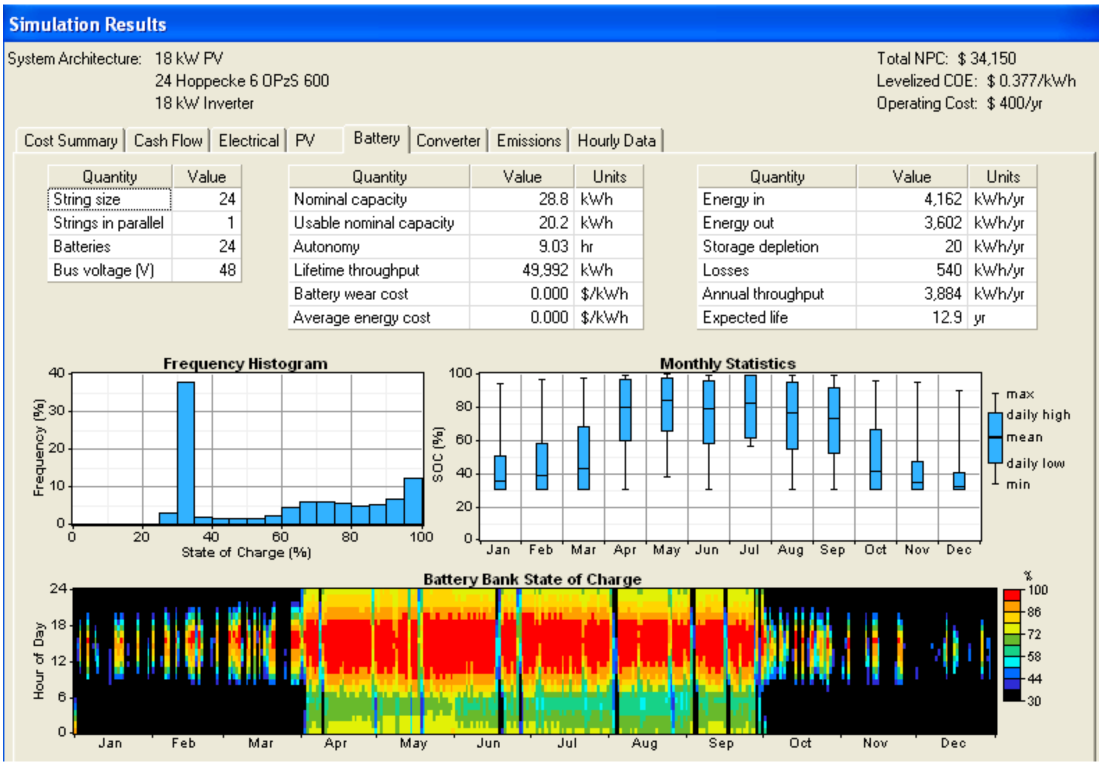
Total NPC: $ 34,150
Levelized COE: $ 0.377/kWh
Operating Cost: $ 400/yr

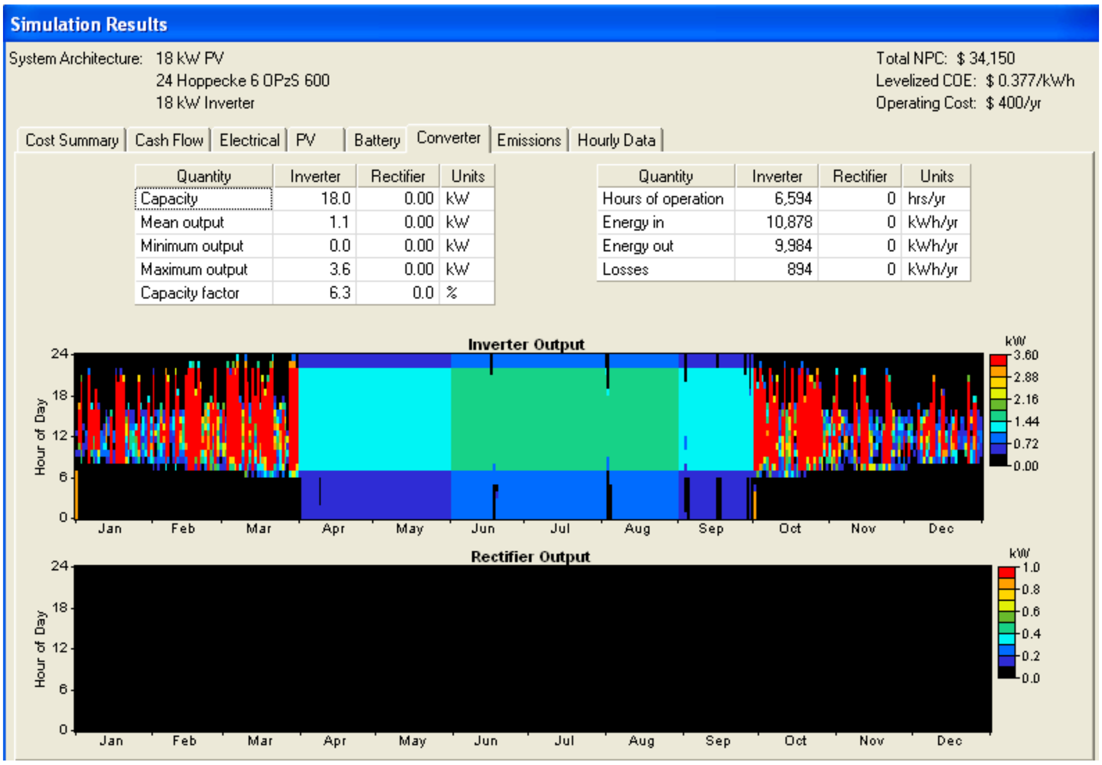
Cost Summary | Cash Flow | Electrical | PV | Battery | Converter | Emissions | Hourly Data

Quantity	Value	Units
Rated capacity	18.0	kW
Mean output	2.5	kW
Mean output	59.7	kWh/d
Capacity factor	13.8	%
Total production	21,789	kWh/yr

Quantity	Value	Units
Minimum output	0.0	kW
Maximum output	18.1	kW
PV penetration	111	%
Hours of operation	4,383	hr/yr
Levelized cost	0.173	$/kWh




Simulation Results
System Architecture: 18 kW PV
24 Hoppecke 6 OPzS 600
18 kW Inverter
Total NPC: $ 34,150
Levelized COE: $ 0.377/kWh
Operating Cost: $ 400/yr
Cost Summary | Cash Flow | Electrical | PV | Battery | Converter | Emissions | Hourly Data
Quantity | Value
String size | 24
Strings in parallel | 1
Batteries | 24
Bus voltage (V) | 48
Quantity | Value | Units
Nominal capacity | 28.8 | kWh
Usable nominal capacity | 20.2 | kWh
Autonomy | 9.03 | hr
Lifetime throughput | 49,992 | kWh
Battery wear cost | 0.000 | $/kWh
Average energy cost | 0.000 | $/kWh
Quantity | Value | Units
Energy in | 4,162 | kWh/yr
Energy out | 3,602 | kWh/yr
Storage depletion | 20 | kWh/yr
Losses | 540 | kWh/yr
Annual throughput | 3,884 | kWh/yr
Expected life | 12.9 | yr
Frequency Histogram
Frequency (%)
State of Charge (%)
Monthly Statistics
SOC (%)
max
daily high
mean
daily low
min
Battery Bank State of Charge
Hour of Day
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec


Simulation Results
System Architecture: 18 kW PV
24 Hoppecke 6 OPzS 600
18 kW Inverter
Total NPC: $ 34,150
Levelized COE: $ 0.377/kWh
Operating Cost: $ 400/yr
Cost Summary | Cash Flow | Electrical | PV | Battery | Converter | Emissions | Hourly Data
Quantity | Inverter | Rectifier | Units
Capacity | 18.0 | 0.00 | kW
Mean output | 1.1 | 0.00 | kW
Minimum output | 0.0 | 0.00 | kW
Maximum output | 3.6 | 0.00 | kW
Capacity factor | 6.3 | 0.0 | %
Quantity | Inverter | Rectifier | Units
Hours of operation | 6,594 | 0 | hrs/yr
Energy in | 10,878 | 0 | kWh/yr
Energy out | 9,984 | 0 | kWh/yr
Losses | 894 | 0 | kWh/yr
Inverter Output
Rectifier Output
Hour of Day
kW
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec

Annex C

PVSYST V5.56

Stand Alone System: Simulation parameters

Project :	**Hybrid PV project**			
Geographical Site	**Bratislava**		**Country**	**Czechoslovakia**
Situation	Latitude	48.1°N	Longitude	17.1°E
Time defined as	Legal Time	Time zone UT+1	Altitude	142 m
	Albedo	0.20		
Meteo data :	Bratislava, Synthetic Hourly data			

Simulation variant :	**New simulation variant**			
	Simulation date	08/07/12 19h20		

Simulation parameters

Collector Plane Orientation	Tilt	34°	Azimuth	0°

PV Array Characteristics

PV module Si-poly	Model	**CS6P - 250P**		
	Manufacturer	Canadian Solar Inc.		
Number of PV modules	In series	10 modules	In parallel	2 strings
Total number of PV modules	Nb. modules	20	Unit Nom. Power	250 Wp
Array global power	Nominal (STC)	**5.00 kWp**	At operating cond.	4446 Wp (50°C)
Array operating characteristics (50°C)	U mpp	268 V	I mpp	17 A
Total area	Module area	**32.2 m^2**	Cell area	29.2 m^2

PV Array loss factors

Thermal Loss factor	Uc (const)	20.0 W/m^2K	Uv (wind)	0.0 W/m^2K / m/s
=> Nominal Oper. Coll. Temp. (G=800 W/m^2, Tamb=20°C, Wind=1 m/s.)			NOCT	56 °C
Wiring Ohmic Loss	Global array res.	39 mOhm	Loss Fraction	0.2 % at STC
Array Soiling Losses			Loss Fraction	1.0 %
Module Quality Loss			Loss Fraction	1.0 %
Module Mismatch Losses			Loss Fraction	1.0 % at MPP
Incidence effect, ASHRAE parametrization	IAM =	1 - bo (1/cos i - 1)	bo Parameter	0.05

System Parameter	System type	**Stand Alone System**		
Battery	Model	**OPzS solar.power 200**		
	Manufacturer	Hoppecke		
Battery Pack Characteristics	Voltage	48 V	Nominal Capacity	151 Ah
	Nb. of units	4 in series		
	Temperature	Fixed (20°C)		
Regulator	Model	XW MPPT 60 800		
	Manufacturer	Schneider Electric		
	Technology	MPPT converter	Temp coeff.	-5.0 mV/°C/elem.
Converter	Maxi and EURO efficiencies	91.8/91.5 %		
Battery Management Thresholds	Charging	550.0/195.0 V	Discharging	16.0/48.0 V
	Back-Up Genset Command	47.3/51.6 V		

User's needs :	Daily household consumers	Constant over the year		
	average	13.6 kWh/Day		

PVSYST V5.56

Stand Alone System: Detailed User's needs

Project : **Hybrid PV project**

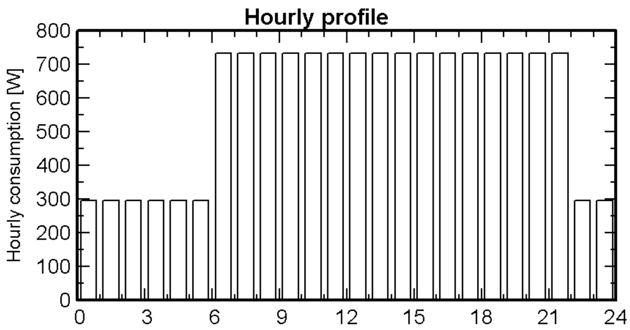
Simulation variant : **New simulation variant**

Main system parameters	System type	**Stand alone**		
PV Field Orientation	tilt	34°	azimuth	0°
PV Array	Nb. of modules	20	Pnom total	**5.00 kWp**
Battery	Model	OPzS solar.power 200	Technology	vented, tubular
battery Pack	Nb. of units	4	Voltage / Capacity	**48 V / 151 Ah**
User's needs	Daily household consumers	Constant over the year	global	5142 kWh/year

Daily household consumers, Constant over the year, average = 14.1 kWh/day

Annual values

	Number	Power	Use	Energy
Domestic appliances	1	587 W/app	24 h/day	14088 Wh/day
Total daily energy				14088 Wh/day



PVSYST V5.56	SolarEnergia, s.r.o.	08/07/12

Stand Alone System: Main results

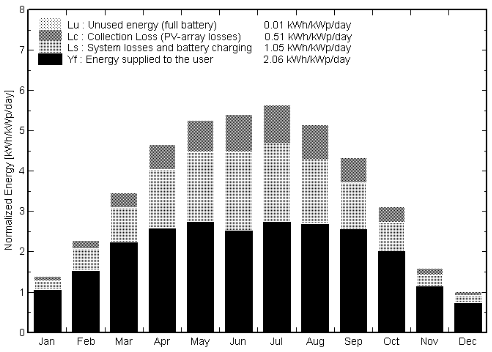
Project : **Hybrid PV project**

Simulation variant : **New simulation variant**

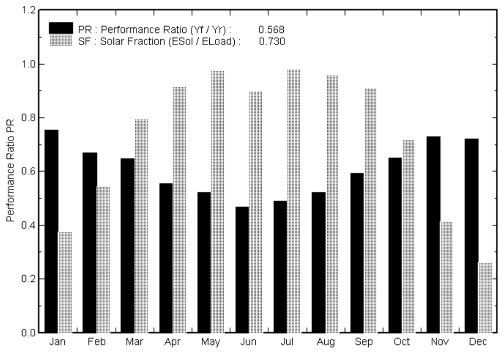
Main system parameters	System type	**Stand alone**		
PV Field Orientation	tilt	34°	azimuth	0°
PV Array	Nb. of modules	20	Pnom total	**5.00 kWp**
Battery	Model	OPzS solar.power 200	Technology	vented, tubular
battery Pack	Nb. of units	4	Voltage / Capacity	**48 V / 151 Ah**
User's needs	Daily household consumers	Constant over the year	global	5142 kWh/year

Main simulation results				
System Production	**Available Energy**	**5193 kWh/year**	Specific prod.	1039 kWh/kWp/year
	Used Energy	3755 kWh/year	Excess (unused)	11 kWh/year
	Performance Ratio PR	56.8 %	Solar Fraction SF	73.0 %
Loss of Load	Time Fraction	28.8 %	Missing Energy	1387 kWh/year

Normalized productions (per installed kWp): Nominal power 5.00 kWp



Performance Ratio PR and Solar Fraction SF



New simulation variant

Balances and main results

	GlobHor	GlobEff	E Avail	EUnused	E Miss	E User	E Load	SolFrac
	kWh/m²	kWh/m²	kWh	kWh	kWh	kWh	kWh	
January	28.0	42.2	182.9	1.096	272.7	164.1	436.7	0.376
February	44.8	62.1	266.5	0.603	179.8	214.6	394.5	0.544
March	85.9	104.0	441.1	0.705	88.5	348.3	436.7	0.797
April	126.9	136.0	556.8	0.763	34.7	388.0	422.6	0.918
May	163.1	158.1	635.0	0.780	10.7	426.1	436.7	0.976
June	169.8	157.4	615.2	1.275	42.5	380.2	422.6	0.899
July	179.2	169.8	664.4	1.238	8.6	428.1	436.7	0.980
August	150.4	155.3	607.2	0.919	18.9	417.9	436.7	0.957
September	106.8	126.2	509.8	0.256	37.6	385.0	422.6	0.911
October	68.5	93.9	388.3	0.808	121.7	315.0	436.7	0.721
November	31.5	46.2	195.4	0.791	248.5	174.2	422.6	0.412
December	20.6	30.5	130.8	1.825	322.8	114.0	436.7	0.261
Year	1175.5	1281.9	5193.4	11.058	1386.8	3755.4	5142.1	0.730

Legends:

GlobHor	Horizontal global irradiation	E Miss	Missing energy
GlobEff	Effective Global, corr. for IAM and shadings	E User	Energy supplied to the user
E Avail	Available Solar Energy	E Load	Energy need of the user (Load)
EUnused	Unused energy (full battery) loss	SolFrac	Solar fraction (EUsed / ELoad)

PVSYST V5.56	SolarEnergia, s.r.o.	08/07/12

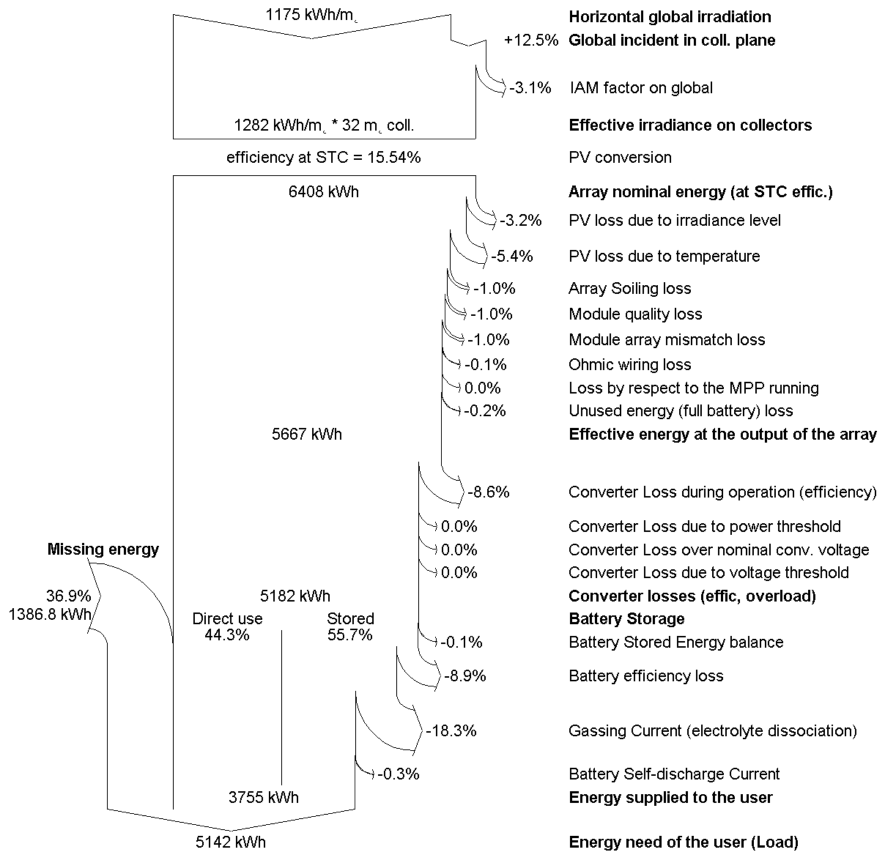
Stand Alone System: Loss diagram

Project : **Hybrid PV project**

Simulation variant : **New simulation variant**

Main system parameters	System type	**Stand alone**		
PV Field Orientation	tilt	34°	azimuth	0°
PV Array	Nb. of modules	20	Pnom total	**5.00 kWp**
Battery	Model	OPzS solar.power 200	Technology	vented, tubular
battery Pack	Nb. of units	4	Voltage / Capacity	**48 V / 151 Ah**
User's needs	Daily household consumers	Constant over the year	global	5142 kWh/year

Loss diagram over the whole year



Annex D

Years of operation	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Revenues from Green Bonus		505	502	500	497	495	492	490	487	485	483	480	478	475	473	471
Revenues from Electricity Sold to Grid		278	276	275	273	272	271	269	268	267	265	264	263	261	260	259
Total Revenues		**782**	**779**	**775**	**771**	**767**	**763**	**759**	**755**	**752**	**748**	**744**	**740**	**737**	**733**	**729**
Gross Margin		**782**	**779**	**775**	**771**	**767**	**763**	**759**	**755**	**752**	**748**	**744**	**740**	**737**	**733**	**729**
Periodic Technical Revisions		80	82	85	87	90	93	96	98	101	104	108	111	114	117	121
Periodic Watering of Batteries		100	103	106	109	113	116	119	123	127	130	134	138	143	147	151
Mandatory Electrical Revisions		20	21	21	22	23	23	24	25	25	26	27	28	29	29	30
Total Operating Expenses		**200**	**206**	**212**	**219**	**225**	**232**	**239**	**246**	**253**	**261**	**269**	**277**	**285**	**294**	**303**
EBITDA		582	573	562	552	542	531	520	509	498	487	475	464	452	439	427
Depreciation		1 982	1 982	1 982	1 982	1 982	1 982	0	322	322	645	645	645	645	322	322
EBIT		-1 399	-1 409	-1 419	-1 429	-1 440	-1 450	520	187	176	-158	-169	-181	-193	117	105
Interest Expenses		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
EBT		-1 399	-1 409	-1 419	-1 429	-1 440	-1 450	520	187	176	-158	-169	-181	-193	117	105
Cummulated Profit / Loss		-1 399	-2 808	-4 227	-5 657	-7 096	-8 547	-8 026	-7 839	-7 663	-7 821	-7 990	-8 171	-8 364	-8 247	-8 142
Personal Income Tax (19%)		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
After Tax Profit		1 399	2 808	4 227	5 657	7 096	8 547	8 026	7 839	7 663	7 821	7 990	8 171	8 364	8 247	8 142
Maintenance CAPEX		0	0	0	0	0	0	0	1 934	0	1 934	0	0	0	0	0
Savings from Lower Grid Purchases		514	527	540	554	568	582	596	611	626	642	658	674	691	708	725
Cash flow	-11 889	1 097	1 100	1 103	1 106	1 109	1 113	1 117	-814	1 124	-805	1 133	1 138	1 142	1 147	1 152
Cummulated Cash Flow	-11 889	-10 792	-9 693	-8 590	-7 484	-6 375	-5 262	-4 145	-4 959	-3 835	-4 640	-3 507	-2 369	-1 227	-80	1 072
Discounted Cash Flow (DCF)	-11 889	1 045	997	953	910	869	830	793	-551	725	-494	662	633	606	579	554

Internal Rate of Return (IRR)	**1,13%**
NPV of Equity	**-2 777**
Simple payback time	**14,08**
Discounted payback time	**20,01**

Annex E

Years of operation	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Revenues from Green Bonus		1 342	1 336	1 329	1 322	1 316	1 309	1 302	1 296	1 289	1 283	1 277	1 270	1 264	1 258	1 251
Revenues from Electricity Sold to Grid		2 014	2 004	1 994	1 984	1 974	1 964	1 954	1 944	1 935	1 925	1 915	1 906	1 896	1 887	1 877
Total Revenues		**3 356**	**3 339**	**3 322**	**3 306**	**3 289**	**3 273**	**3 257**	**3 240**	**3 224**	**3 208**	**3 192**	**3 176**	**3 160**	**3 144**	**3 129**
Gross Margin		**3 356**	**3 339**	**3 322**	**3 306**	**3 289**	**3 273**	**3 257**	**3 240**	**3 224**	**3 208**	**3 192**	**3 176**	**3 160**	**3 144**	**3 129**
Periodic Technical Revisions		80	82	85	87	90	93	96	98	101	104	108	111	114	117	121
Periodic Watering of Batteries		300	309	318	328	338	348	358	369	380	391	403	415	428	441	454
Mandatory Electrical Revisions		20	21	21	22	23	23	24	25	25	26	27	28	29	29	30
Total Operating Expenses		**400**	**412**	**424**	**437**	**450**	**464**	**478**	**492**	**507**	**522**	**538**	**554**	**570**	**587**	**605**
EBITDA		2 956	2 927	2 898	2 869	2 839	2 809	2 779	2 748	2 717	2 686	2 654	2 622	2 590	2 557	2 523
Depreciation		6 104	6 104	6 104	6 104	6 104	6 104	0	743	743	1 737	1 737	1 737	1 737	994	994
EBIT		-3 148	-3 177	-3 206	-3 235	-3 265	-3 295	2 779	2 005	1 974	949	917	885	853	1 563	1 530
Interest Expenses		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
EBT		-3 148	-3 177	-3 206	-3 235	-3 265	-3 295	2 779	2 005	1 974	949	917	885	853	1 563	1 530
Cummulated Profit / Loss		-3 148	-6 325	-9 530	-12 765	-16 030	-19 325	-16 546	-14 541	-12 567	-11 618	-10 701	-9 816	-8 963	-7 400	-5 870
Personal Income Tax (19%)		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
After Tax Profit		3 148	6 325	9 530	12 765	16 030	19 325	16 546	14 541	12 567	11 618	10 701	9 816	8 963	7 400	5 870
Maintenance CAPEX									4 461		4 968	0	0	0	0	0
Savings from Lower Grid Purchases		1 368	1 402	1 437	1 472	1 509	1 546	1 585	1 624	1 665	1 706	1 748	1 792	1 836	1 882	1 929
Cash flow	-36 623	4 324	4 329	4 335	4 341	4 348	4 356	4 364	-88	4 382	-576	4 403	4 414	4 426	4 439	4 452
Cummulated Cash Flow	-36 623	-32 299	-27 970	-23 635	-19 294	-14 946	-10 591	-6 227	-6 315	-1 933	-2 509	1 893	6 307	10 733	15 172	19 624
Discounted Cash Flow (DCF)	-36 623	4 118	3 926	3 745	3 571	3 407	3 250	3 101	-60	2 825	-354	2 574	2 458	2 347	2 242	2 142

Internal Rate of Return (IRR)	**6,10%**
NPV of Equity	**2 670**
Simple payback time	**10,57**
Discounted payback time	**12,73**

Annex F

Scenario	Change	FiT (EUR/kWh)	IRR (%)	NPV (EUR)	DPT (yrs)	Sensitivity of IRR	Sensitivity of NPV	Sensitivity of DPT
1	-10%	0,17509	-0,42%	-3 792,0	>15	-141,2%	-33,1%	N/A
2	+10%	0,21399	2,61%	-1 761,0	>15	155,9%	38,2%	N/A
3	27,4%	0,24775	5,00%	0,0	15,00	390,2%	100,0%	N/A
4	-69,1%	0,06011	N/A	-9 791,0	>15	N/A	-243,8%	N/A

Scenario	Change	CPE (EUR/kWh)	IRR (%)	NPV (EUR)	DPT (yrs)	Sensitivity of IRR	Sensitivity of NPV	Sensitivity of DPT
1	-10%	0,12330	0,16%	-3 400,0	>15	-84,3%	-19,4%	N/A
2	+10%	0,15070	2,06%	-2 153,0	>15	102,0%	24,4%	N/A
3	44,5%	0,19800	5,00%	0,0	15,00	390,2%	100,0%	N/A

Scenario	Change	Invest. costs (EUR)	IRR (%)	NPV (EUR)	DPT (yrs)	Sensitivity of IRR	Sensitivity of NPV	Sensitivity of DPT
1	-10%	10 700,3	2,59%	-1 588,0	>15	153,9%	44,2%	N/A
2	+10%	13 078,2	-0,11%	-3 965,0	>15	-110,8%	-39,2%	N/A
3	-23,4%	9 113,0	5,00%	0,0	15,00	390,2%	100,0%	N/A
4	-17%	9 907,7	3,72%	-795,0	>15	264,7%	72,1%	N/A

Annex G

Scenario	Change	FiT (EUR/kWh)	IRR (%)	NPV (EUR)	DPT (yrs)	Sensitivity of IRR	Sensitivity of NPV	Sensitivity of DPT
1	-10%	0,17509	5,27%	642,0	14,69	-12,3%	-76,0%	6,8%
2	+10%	0,21399	6,92%	4 697,0	12,90	15,1%	75,9%	-6,3%
3	-13,2%	0,16893	5,00%	0,0	14,87	-16,8%	-100,0%	8,1%
4	-69,1%	0,06011	-0,19%	-11 342,0	>15	-103,2%	-524,8%	N/A

Scenario	Change	CPE (EUR/kWh)	IRR (%)	NPV (EUR)	DPT (yrs)	Sensitivity of IRR	Sensitivity of NPV	Sensitivity of DPT
1	-10%	0,12330	5,42%	1 011,0	14,48	-9,8%	-62,1%	5,23%
2	+10%	0,15070	6,76%	4 328,0	13,10	12,5%	62,1%	-4,80%
3	-16,1%	0,11494	5,00%	0,0	14,95	-16,8%	-100,0%	8,65%

Scenario	Change	Invest. costs (EUR)	IRR (%)	NPV (EUR)	DPT (yrs)	Sensitivity of IRR	Sensitivity of NPV	Sensitivity of DPT
1	-10%	32 960,5	7,84%	6 332,0	12,13	30,4%	137,2%	-11,8%
2	+10%	40 285,1	3,57%	-3 663,0	16,71	-40,6%	-237,2%	21,4%
3	7,3%	39 292,0	5,00%	0,0	14,96	-16,8%	-100,0%	8,7%
4	-17%	30 519,0	9,19%	8 773,0	11,04	52,9%	228,6%	-19,8%