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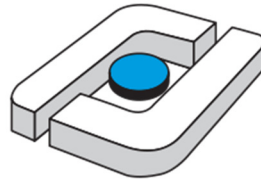
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CAPACIDAD DE ALMACENAMIENTO EN LA INDUSTRIA

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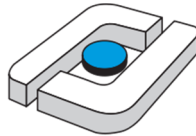
Master thesis

**East-west photovoltaic systems with
small storage capacity in industry**

Submitted by

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Abstract/ Zusammenfassung/ Resumen

Abstract

The target of the present project is to adjust the generated profile of an E-W photovoltaic system with small power storage capacity to the load profile of different industries in Germany.

The emphasis is to be placed on the following work packages:

- Comparison of the performance of an E-W PV system facing the typical south PV installation performance
- Simulation of an E-W PV installation with storage capacity in a company based on MATLAB / Simulink software
- Economic optimization

The results obtained show that it is never economic to install an E-W PV field instead of a south PV installation, if the only advantage is the expected broadening of the curve.

Zusammenfassung

Das Ziel dieses Projektes ist es, das erzeugte Profil einer Ost-West PV-Anlage mit kleinen Speicherkapazität an das Lastprofil von verschiedenen Industrien in Deutschland anzupassen.

Der Schwerpunkt liegt auf den folgenden Arbeitspaketen:

- Vergleich der Leistung eines Ost-West PV-Systems mit der Leistung der typischen Süden PV-Anlage
- Simulation einer Ost-West PV-Anlage mit Speicherkapazität in einem Unternehmen gründet auf der MATLAB / Simulink Software
- Wirtschaftliche Optimierung

Die erhaltenen Ergebnisse zeigen, dass es sich wirtschaftlich nie lohnt, eine Ost-West PV-Feld anstelle einer PV-Anlage nach Süden zu installieren, wenn der einzige Vorteil die erwartete Verbreiterung der Kurve ist.

Resumen

El objetivo del presente proyecto es ajustar el perfil generado por un sistema fotovoltaico con orientación este-oeste que dispone de una batería al perfil de demanda de distintas industrias en Alemania.

Se ha puesto especial énfasis a los siguientes paquetes de trabajo:

- Comparación de la eficiencia de un sistema fotovoltaico este-oeste frente a los resultados obtenidos con la típica orientación sur
- Simulación de una instalación fotovoltaica este-oeste con una batería en una industria, basada en el software MATLAB / Simulink
- Optimización económica

Los resultados obtenidos muestran que nunca es económico instalar un campo fotovoltaico este-oeste en vez de una instalación con orientación sur, en caso de que la única ventaja esperada sea el ensanche de la curva de generación de potencia.

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List of symbols

Symbols

| | |
|------------|--------------------------------------|
| A | Area, m^2 |
| G | Irradiance, W/m^2 |
| H | Irradiation, Ws/m^2 , kWh/m^2 |
| E | Energy, $Ws = J$, kWh |
| α_s | Azimuth angle of a surface, $^\circ$ |
| γ_s | Tilt angle of a surface, $^\circ$ |
| I | Current, A |
| I_{sc} | Short Circuit Current, A |
| P | Power, W |
| R | Resistance, Ω |
| U | Voltage, V |
| U_{oc} | Open Circuit Voltage, V |
| η | Efficiency |

Abbreviations

| | |
|-----------|----------------------------------|
| PV | Photovoltaic |
| E-W | East-West |
| RE | Renewable Energy |
| STC | Standard Test Conditions |
| AM | Air Mass |
| FIT | Feed In Tariff |
| SOC | State Of Charge |
| MPP | Maximum Power Point |
| MPPT | Maximum Power Point Tracking |
| P_{mpp} | Power at the Maximum Power Point |
| GUI | Graphical User Interface |

1 Introduction and Task

1.1 General Background

Governments around the world are witnessing a steadily rising demand on global electric power. We are facing a crucial situation because as the world population grows the electricity demand will also increase, but at the same time, we will need to reduce our electricity consumption to fight against global warming. To face this challenge, regulatory guidelines are being adopted to foment the adoption of best practices by utilities in terms of the Smart Grid and RE applications.

A smart grid is a low voltage grid-connected system which consists of an aggregation of micro-generators, loads and storage devices operating as a single system that provides both electrical and heat energy [12]. This organization allows the consumers to monitor and control their energy by its consumption, storage or sale to the grid. The concept arose through renewable energies and it is encompassed within what is known as distributed generation, which has many advantages over conventional systems in terms of technical, economic and environmental approach (if its elements are managed and coordinated efficiently).

Several investigations are being made for improving the system and reducing its cost in order to incentive its spread among the consumers. As a result, the PV systems are becoming much easier to install but the efficiency of solar modules is still low (between 7 and 18%). The idea of this report is developed within this context of distributed generation performance improvement. In this system, particularly for the load profile of certain industries, the coordinated use of east-west PV devices with small storage capacity allows to increase the self-consumption rate of solar power, which results in a particularly efficient utilization of RE.



1.2 Task

The target of the present project is to adjust the generated profile of an east-west PV system with small power storage capacity to the load profile of some industries of Germany. Another aim is to achieve an economic optimization of power reduction (peak shaving) and self-consumption in dependence on the load profile while making a transferable solution for different load profiles of different industries.

The emphasis is to be placed on the following work packages:

- Comparison of the performance of an E-W PV system facing the typical south PV installation performance
- Simulation of an E-W PV installation with storage capacity in a company based on MATLAB / Simulink software
- Economic optimization

1.3 Method

To achieve this goal it is necessary to make a model of the complete system which includes as main components an E-W orientated solar PV device, a battery and a specific consumer. In addition, it must consider the grid as an external source with a specific load profile.

In the attempt to simulate this model, a research of the different simulation software currently available in the market is made.

2 PV Systems

2.1 Operation and Components

Photovoltaic power systems are very modular, which not only makes for easy transportation and rapid installation possible, but also enables easy expansion if power requirements increase. PV systems may comprise some or all of the following basic components:

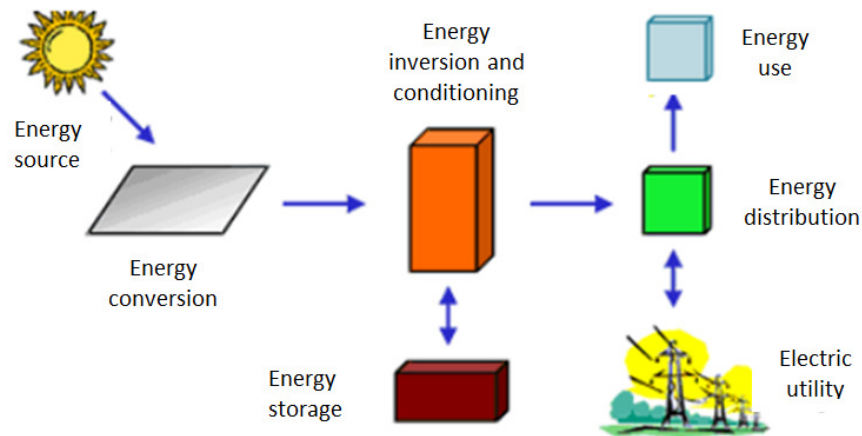


Figure 1: Major PV system components [11]

1. PV generator and support structure
2. Power conditioning equipment (including inverters, control and protection equipment)
3. Power storage (normally batteries)
4. Cables
5. Load
6. Grid connection

The solar PV generating equipment has no moving parts, which keeps maintenance requirements to a minimum and leads to long service lifetimes. The modules themselves are typically expected to operate for about twenty years and should not require much more than occasional cleaning to remove deposits of dirt.

The majority of the other components are generally serviceable for ten or more years if simple preventative maintenance measures are followed. Batteries are currently the “weak-link” in the system and typically need replacement every five years approximately.

2.2 Solar Power Storage

In general, power storage means the de-coupling of energy offer and demand on the time scale and according to this principle, batteries in PV systems are often used for storing energy produced during the day and to supply it to electrical loads as needed (during the night and periods of cloudy weather). Nevertheless, the main benefit of integrating storage with renewable energy that is considered in this project is the capability of covering the peak demands by charging/discharging the battery (charging when the excess electricity is stored, discharging when there is a peak demand). The storage can be charged from the renewable sources or from the grid. The demand of the consumer can be met by the solar source, by the energy storage or by the combinations of these.

The other benefits of solar energy storage are:

- Mitigation of short-term solar power intermittency and minimizing its impacts on voltage, frequency and power fluctuations in power system.
- Lowering the transmission and distribution costs by increasing the confidence in renewable distributed generation.
- Improving power system stability.

In most cases, a battery charge controller is used in these systems to protect the battery from overcharge and over-discharge.

The use of batteries in PV systems differs from the use of batteries in other common battery applications since PV batteries experience both deep cycling and are left at low states of charge for extended periods of time. Typically, the power generated by the solar panels is usually used to charge a lead-acid battery although many other types are used. Nevertheless, there may be found several disadvantages and dangers when using different types of batteries such as chemical burns, flammable gases while charging, batteries are heavy, the electrolyte can evaporate, recycling must be organized, etc.

2.3 Classification

Photovoltaic power systems are generally classified according to their functional and operational requirements, their component configurations, and how the equipment is connected to other power sources and electrical loads. The two principal classifications are grid-connected systems and stand-alone systems.

Firstly, a *grid-connected PV system* injects its power directly into the grid itself. The advantages of this system are the ability to sell excess of energy and the relatively reliable supply provided by the electric grid. Moreover, with a little storage capacity it can also be used to avoid peaks of consumption of production by using the power stored in the battery, and consequently, for saving money.

Secondly, a *stand-alone PV system* is used in isolated locations where the PV is connected directly to the load and normally to the storage system too. The advantages of storage are savings in wiring connections to the grid, the possibility of installing it at any location, energy independence and therefore backup facing emergencies, for example when the utility grid is exposed to blackouts. Nevertheless, this total dependence on the self-generated energy leads obviously to a critical situation in case of a greater energy demand.

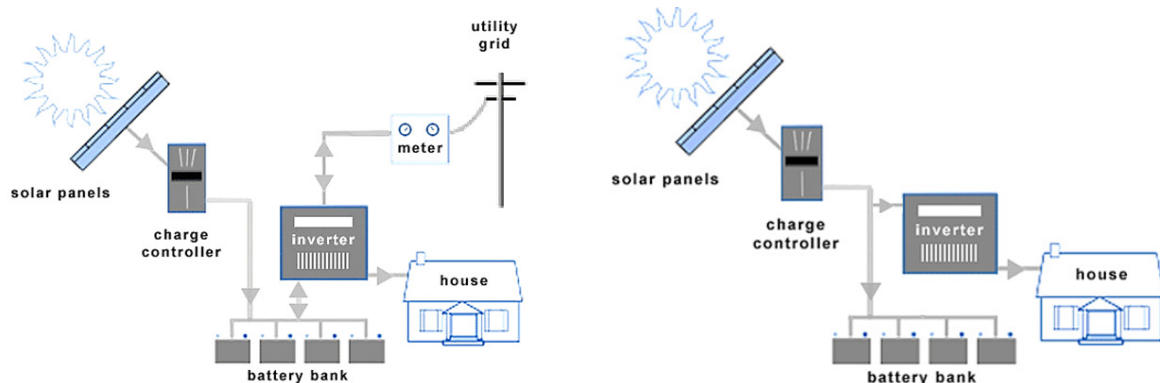


Figure 2: Grid-connected and stand-alone PV systems [1]

2.4 Regulatory Framework

2.4.1 Specifications and Standards for Grid-connected PV Systems

New interconnection requirements for utility-connected PV systems are coming in several European countries in order to support the grid operation and stability. This approach to better integration of photovoltaic systems into the electric power system makes a larger dissemination of renewable energies possible.

National laws, standards and recommendations in different countries have different characteristics. However, for a wide deployment of distributed generation and RE, it is also vital to harmonize the interconnection requirements on a European level and to bring in line the different interests of manufacturers, decentralized power producers and network operators. To carry out this challenging task, there is a European initiative at CENELEC, the European Standardization organization in the field of electrical engineering. One of its major points is grid support of distributed generators: they must contribute to voltage stabilization in order to avoid disconnection in the case of voltage dips.

In Germany, in order to assure the power quality of the grid, the PV grid-connected systems are obliged to meet grid-supporting requirement standards covering the following topics: voltage control, power characteristic parameters (power factor), active and reactive power control, DC current injection, flicker, frequency, current harmonics, fault-ride-through capability and limitation of short-circuit current if necessary [4].

2.4.2 Instruments that Support Photovoltaic Technology

There are two principal investment tools for renewable energies: the feed-in tariff and the quota obligation.

A feed-in tariff (FIT) is an energy supply policy focused on supporting, from a financial point of view, the development of new renewable energy projects by offering long-term purchase agreements for the sale of renewable electricity. These agreements are around 15-20 years in force and concern a guaranteed price for every kilowatt-hour of electricity

produced. There are two dominant ways to structure FIT policy payments: Firstly, the Fixed-Price FIT payment models are independent of market prices and are the most extended, and secondly the Premium-Price FIT payment models, which depend on the market price for electricity and offer a premium above the average spot electricity market price [3].

A quota obligation is an annual obligation on the part of electricity suppliers to hold renewable electricity certificates corresponding to their sale and use of electricity during the previous year. Producers of electricity from renewable energy sources receive an electricity certificate for every MWh of electricity produced. By selling these certificates, the producer receives an extra income in addition to the sale of electricity. This makes it profitable to invest in new renewable electricity production.

2.4.3 Situation in Germany

Within this scenario the German EEG ("Erneuerbare Energien Gesetz" or RE Feed-in Law) model should be mentioned, which came into force in 2000 and was last amended in 2012. This Feed-in Law was based on the following changes: firstly, the purchase prices were based on generation cost, and their level would be constant for 20 years. Secondly, the utilities were forced to participate and finally, rates were designed to decline annually based on expected cost reductions, depending on the year of commissioning [15].

Thanks to this legislation, the generation of electricity from renewable energies was doubled within a few years resulting in PV electricity price drop of up to 40% during peak output times and therefore proving to be the world's most effective policy framework at accelerating the RE deployment.

Nevertheless, savings for consumers meant reductions in the profit margin of big utilities, who reacted by lobbying the government, which unfortunately reduced the FIT considerably in 2012.

Future prospects in Germany are not clear, since in November 2014, feed-in tariffs for a kilowatt-hour of solar power from new PV systems will range from 0.0974 € to 0.1407 € [6].

2.5 East-West PV Systems

2.5.1 Initial Overview

The common yield-optimized PV systems in southern orientation generate their energy during the day in the form of a mountain with midday peak. On the other hand, the industries have rather a flat consumption curve during the day with discrete load peaks, see Figure 3.

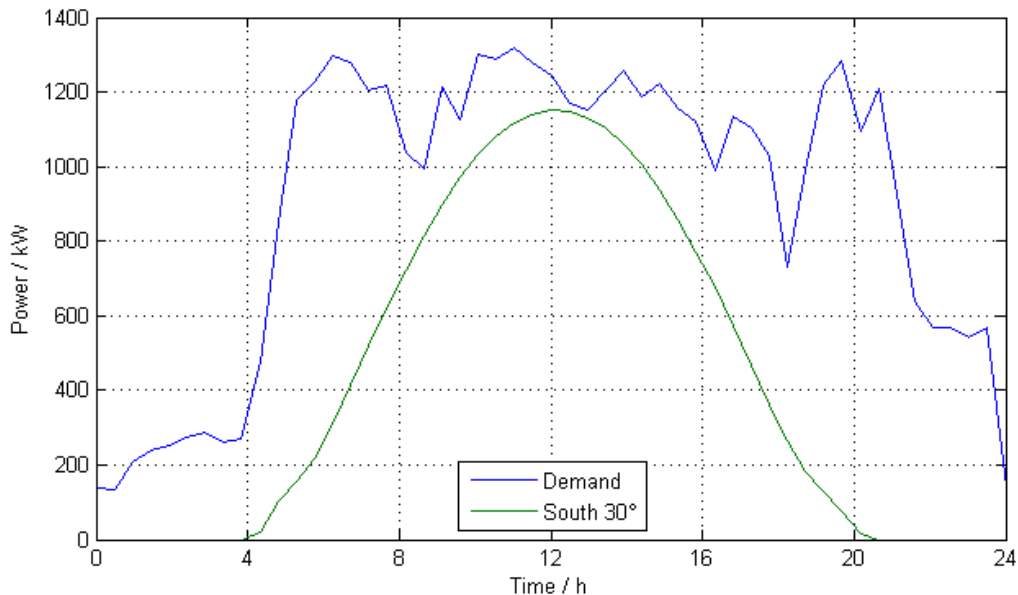


Figure 3: Comparison south tilted PV generation with one industry load profile over a day

The mismatch of these two curves normally prevents the efficient use of the solar power generated by the respective industry, and consequently a high level of self-consumption ratio. As a result, economical PV systems with high self-consumption must be designed rather small; otherwise a higher proportion of the electricity generated must be fed into the grid in and sold at a lower price than the consumption price avoided, which results in a lower profitability.

The solution proposed in this project is the establishment of PV systems with E-W orientation with a low inclination angle in conjunction with commercial self-consumption solutions. Such installations are already common as they have a further advantage facing the common southern orientation: they spread the yield and provide a daily graph that is better adapted to the flat load profile of a company, since the electricity production is shifted into the morning and afternoon hours and the midday peak is therefore reduced. This means that power consumption in the morning and evening can be better covered and it enables the company to have a higher solar power self-consumption. The production is similar to south-facing systems, but smoother; the yield reduction of approximately 8% is taken consciously [19].

In addition, this self-consumption rate can be also increased by a battery which can be smaller in comparison of the one needed for a South orientated system because of the better matching of the generated and the load curve. This battery can also be used for avoiding the load profile peaks that surmount the power contracted from the electric utilities, resulting in a money saving.

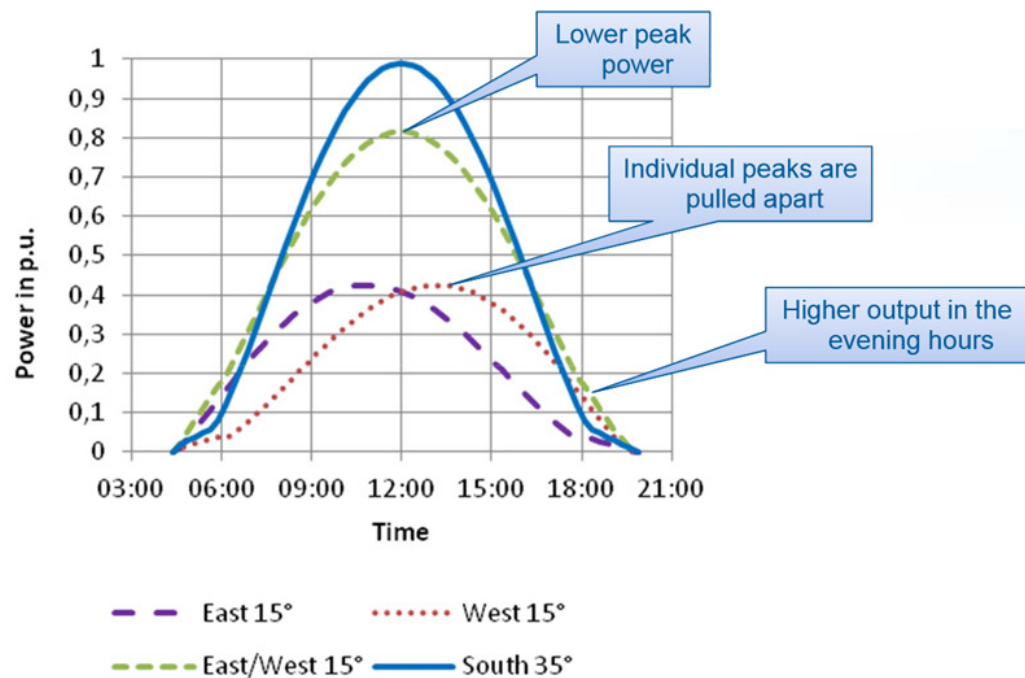


Figure 4: Power vs. time curves obtained with a module south, east or west orientated [16]

2.5.2 Advantages of a Low-tilt E-W PV System with Small Storage Capacity [19]

- East-West orientation spreads the generated profile along the day
- Better adaptation to the consumption profile from an industry
- Increase of the self-consumption up to 100%
- Increase of the solar rate of the consumption
- Peak-shaving by spreading the yield curves
- Peak-shaving by battery
- Smaller battery by yield spread
- Optimization of the profitability
- Better use of the available roof area: the rooftop installation can be almost doubled, as south-faced needs gaps in between the rows, otherwise they shade each other.
- Shading effects are reduced
- Reduction of exposure to wind through the E-W framework positioning of the PV flat roof installation
- Power relief through decentralized self-consumption
- Power relief by temporal balance: the production starts slowly in the morning and declines gently at sunset without generating sharp peaks
- Power relief for the grid through peak shaving and storage, adaption of the PV to the load profile: the utility does not have to face pyramid production.
- Power grid minimization
- Less stress on components and less losses via heat flow since the modules are not perfectly aligned towards de sun
- In case of morning dew or problems in noon like cloud or mist, the system has plenty of time to recover during either the morning or the late afternoon (with perfectly aligned south-faced, good production conditions must be met two hours before noon)
- These advantages promote the integration possibilities of solar technology in the Smart Grid and thus the climate protection.

2.5.3 East-west Systems Currently Used in the Industry

The Hölzengraben project is a particularly ambitious PV plant for commercial self-consumption is located the urban area of Kaiserslautern in south-western Germany and was assigned by WVE GmbH to ICB SOLAR AG.

The solar park is, for the time being, the largest system with an east-west orientation ever built with 6.4 MW_p installed capacity. A total of 25400 modules were installed, which generate almost 6000 MWh of electricity annually. That corresponds to CO₂ savings of around 3700 tons a year.

The two industrial consumers have an exclusive locational advantage due to their 1200 m proximity to the solar power plant which allows them to have a direct wiring link.



Figure 5: Photographs of the Hölzengraben project

3 Selection of a Suitable Simulation Software

As already said, in this project an E-W PV grid-connected system with a small storage capacity is considered, in which the electricity supply for the industry is ensured by the grid and the solar system and the battery allows avoiding consumption peaks. This model is schematically presented in the Figure 6:

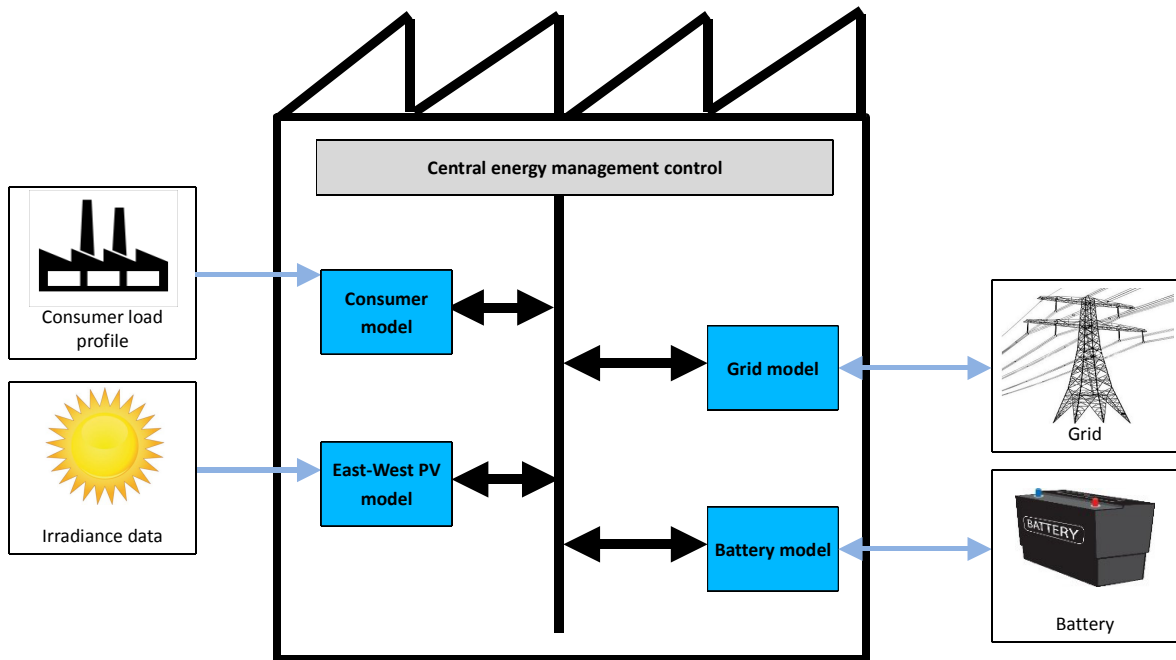


Figure 6: Synoptic model of the system

It is necessary to build a model of this whole system in order to simulate it and obtain the corresponding results afterwards. Therefore, in this chapter the research of appropriate simulation software is exposed and the first attempts of modelling are reported.

3.1 Research

3.1.1 Simulation Tools

In this section, a brief overview of the different simulation tools for PV systems is made. They are divided in two categories: specific and generic tools. Nevertheless, even though this classification has been made for this report, it may be advisable to ignore these

categories and spend a few minutes reading the contents of each package to find out which one fits best.

3.1.1.1 Specific PV Simulation Tools

By these specific tools, the user only needs to specify the type and dimensions of each component and the software will provide a detailed analysis of the system. Here a list of the specific simulation tools with their respective features is presented in the Table 1:

Table 1: Specific simulation tools for PV systems

| | Developer | Cost/ License | Website |
|---------------------------------|--|--|---|
| RETScreen | Natural Resources Canada | Free | www.etscreen.net |
| HOMER | National Renewable Energy Laboratory, USA | Free | www.nrel.gov/homer |
| INSEL | Insel Company, Oldenburg, Germany | 1700 € for full version; 85 € for students | http://www.insel.eu |
| TRNSYS | University of Wisconsin, Madison, USA | · Free demo version · \$ 2100 for students | http://sel.me.wisc.edu/trnsys |
| NREL Solar Advisor Model | National Renewable Energy Laboratory, Washington | Free | https://www.nrel.gov/analysis/sam/background.html |
| Pvsyst | Institute of Environmental Sciences (ISE), Switzerland | 900 CHF for one license; 150 CHF for additional | http://www.pvsyst.com/5.2/index.php |
| SolarDesignTool | Verdiseno, Inc, Santa Cruz, USA | Free version available | http://www.solardesigntool.com/ |
| ESP-r 11.5 | University of Strathclyde, Scotland | Free | http://www.esru.strath.ac.uk/Programs/ESPr.htm |
| SolarPro | Laplace System Co., Ltd, Japan | \$ 1,900 for students | http://www.lapsys.co.jp/english/ |
| PV DesignPro-G | Mau Solar Energy Software Corporation, Haiku, USA | \$ 249.00 for Solar Design Studio | http://www.mausolarsoftware.com/ |
| PV*SOL Expert | Dr. Valentin Energie Software, Germany | 2456 € for 20 for educational licenses | http://www.valentin.de/en/products/photovoltaics/12/pv-sol-expert |

From this list TRNSYS was chosen because of its optimal graphical user interface (GUI), its large building model libraries with ready-made PV components, its fast computation time and its free demo available.

3.1.1.2 Generic Tools with Open Architecture

By the generic tools, the user is able to modify existing routines and include new ones, and the software has a higher flexibility in the interaction between its components.

Table 2: Generic simulation tools for PV systems

| | Developer | Cost/ License | Website |
|-----------------------------|---|------------------------|---|
| MATLAB/ Simulink | The MathWorks Inc., Massachusetts, USA | 6000 € for one license | http://www.mathworks.de |
| Modelica | Modelica Association | Free | www.modelica.org |
| Scilab/ Xcos | Scilab Enterprises | Free | http://www.scilab.org/ |

This kind of software requires a more mathematical language. On the other hand, since the required model involves different components that are unlikely to be found in the same software, the great flexibility of these generic tools may be favorable. Therefore, the three of them are considered in the next section.

3.1.2 Evaluation and Selection

The Table 3 presents the different advantages and disadvantages analysed from each software selected so far:

Table 3: Evaluation and selection of simulation tools for PV systems

| Software | + | - |
|-----------------------------|--|--|
| TRNSYS | <ul style="list-style-type: none"> • Photovoltaic approach • GUI | <ul style="list-style-type: none"> • Not intuitive |
| Modelica | <ul style="list-style-type: none"> • Free | <ul style="list-style-type: none"> • Complicated language • More orientated to automotive and mechanical applications • Extra pay for GUI |
| MATLAB/ Simulink | <ul style="list-style-type: none"> • Familiar to this working group • Optional packages for specific apps • GUI | <ul style="list-style-type: none"> • Very expensive |
| Scilab/ Xcos | <ul style="list-style-type: none"> • Free • Similar to MATLAB/Simulink • Optional packages for specific apps | <ul style="list-style-type: none"> • Available packages unknown |

After this brief review, TRNSYS and MATLAB were chosen in order to make the first attempts of simulation. TRNSYS is selected mainly because of its photovoltaic approach and MATLAB because of its huge flexibility, solving capability and great mature state of development.

3.2 First Attempts of Simulation with TRNSYS

This software is used to simulate the behaviour of transient systems. It can be used not only to model thermal and electrical energy systems but also for other dynamic systems such as traffic flow or biological processes. It can be used for a wide range of applications that are mentioned in the TRNSYS official website [18] but for the present report only energy storage devices (batteries) and PV systems are taken into account.

In the next section, there are the results of the first simulation attempt of our system with only PV modules and a battery as main components. After that, the features of this application are revised in more detail, accompanied by some screenshots of the graphic user interface. This description includes advantages and problems found during the course of the previous simulation.

3.2.1 Demonstration of TRNSYS 17 DEMO

The features of this demo version are:

- Limitation to 5 different components.
- It contains several examples that can be run.
- Possibility of changing the parameters of the components to see the effect on the performance of the system.



Figure 7 shows the first attempt of making a model of our system with a PV installation and a battery as main components. The irradiance data are connected to the PV arrays, which have a directed link to the battery and to the plotter.

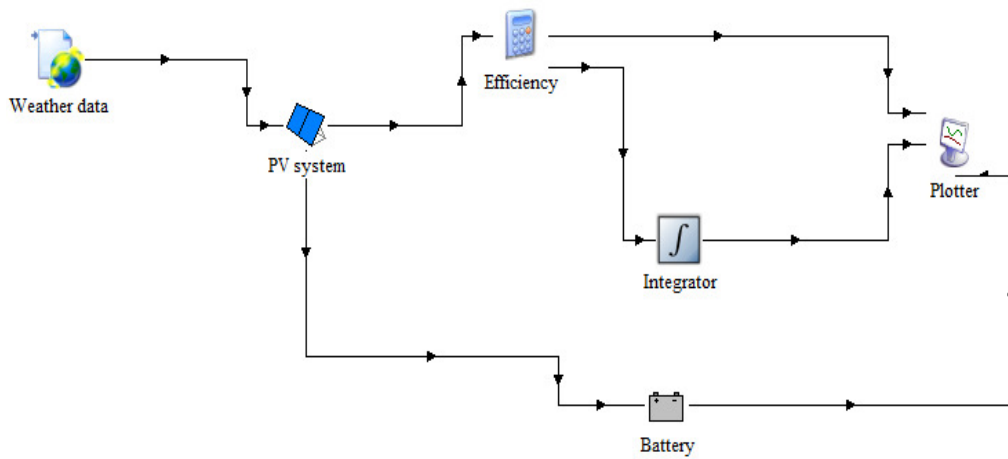


Figure 7: TRNSYS simulation: Screen shot of a model from a PV system with a battery

Three days are simulated, and the results obtained are in the Figure 8: the power and the total energy curves obtained from the PV system in red and blue respectively and in fuchsia the power storage by the battery.

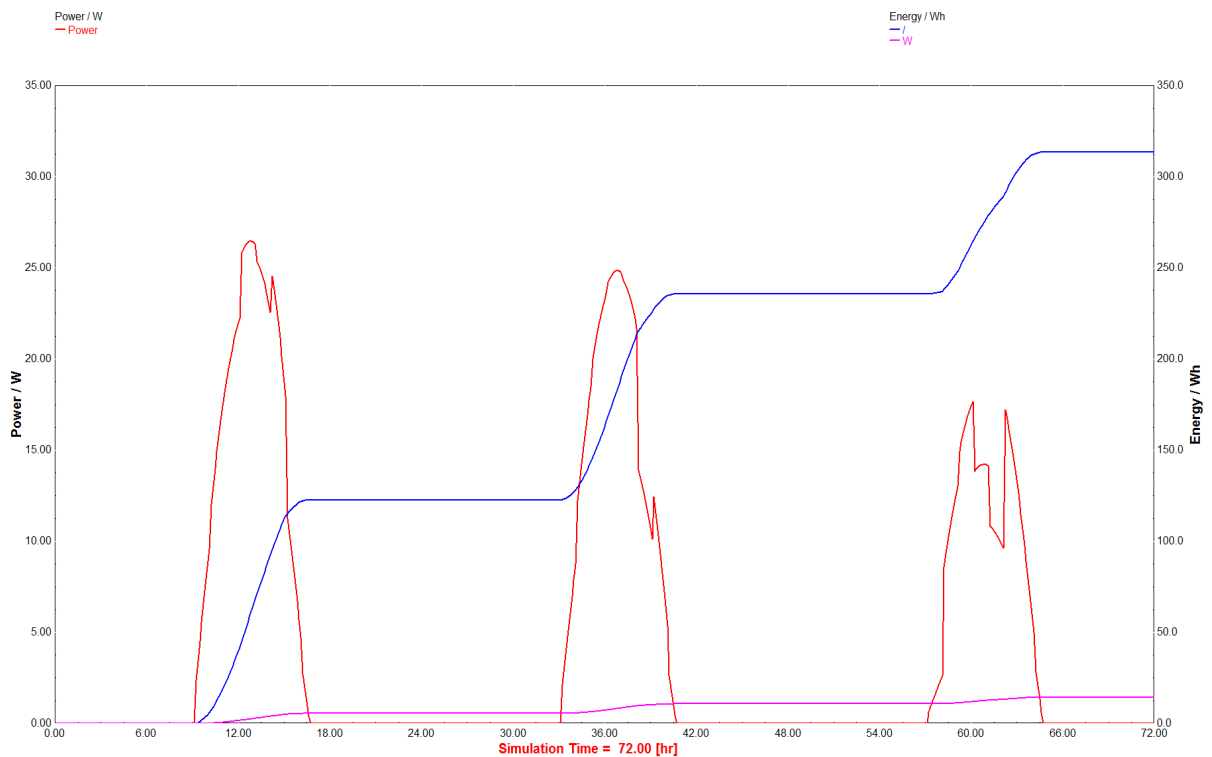


Figure 8: TRNSYS simulation: Power and energy curves of the PV system and power storage by the battery over three days

3.2.2 Advantages, Drawbacks and Conclusion

3.2.2.1 Advantages

- Many ready-made components
 - Extensive configuration options for each component
- Intuitive structure by block diagrams
 - Components are simply connected
 - Inputs and outputs may be defined

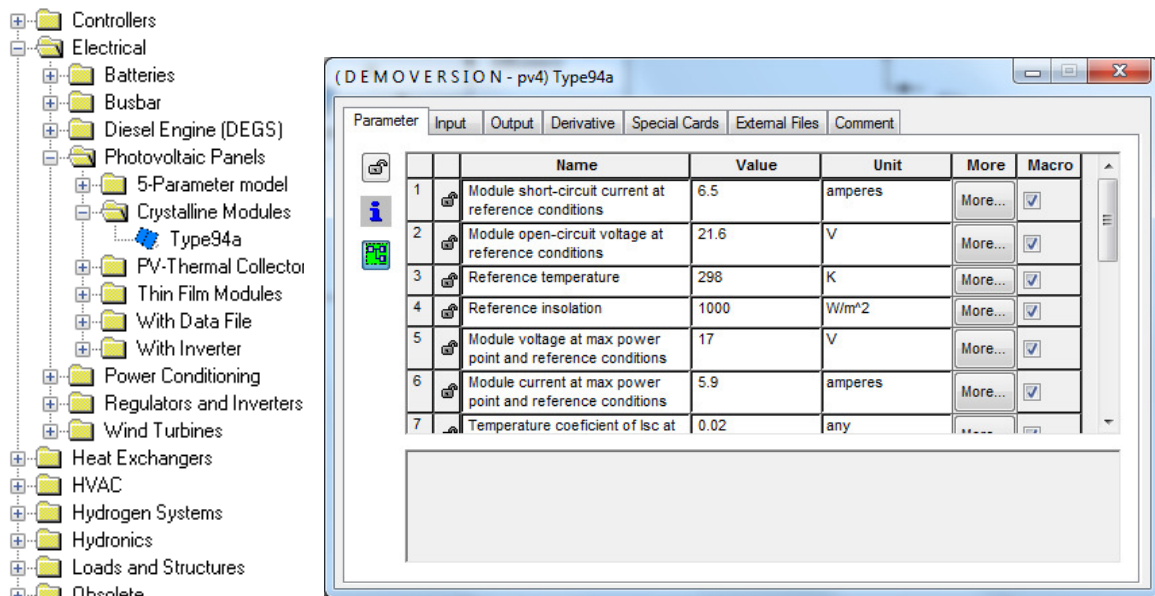


Figure 9: TRNSYS simulation: library components and PV block parameters

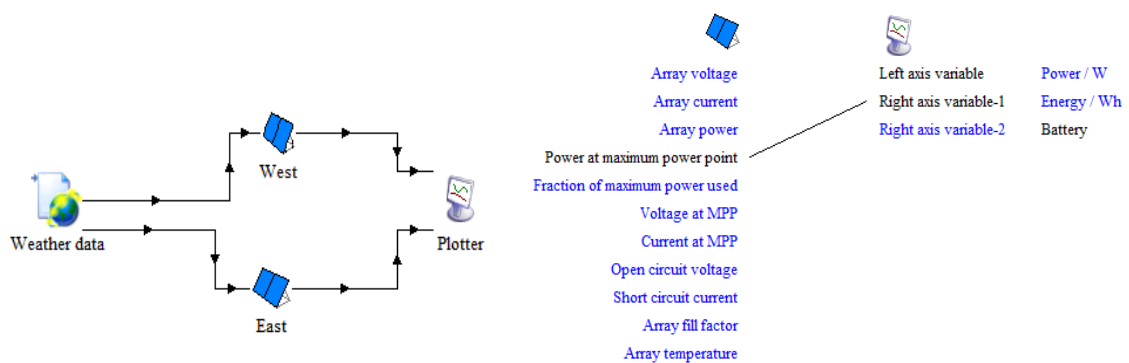


Figure 10: TRNSYS simulation: Examples of a block diagram and definition of in/outputs

3.2.2.2 Drawbacks

- Lack of documentation
 - Components inadequately described
 - Examples non-traceable and partly not feasible in the demo
- Complicated operation
 - Nested and confusing structure
 - Many parameters seem to be not adjustable
- Results are illogical
 - Problems with the units
 - The change of parameters has partially no effect

3.2.2.3 Conclusion

After this brief check of TRNSYS it is shown that some of the drawbacks are unacceptable and in addition, its architecture is quite limited for our necessities. Therefore the decision to abandon this software is taken and from now on all the simulations will be done with MATLAB, which is already a familiar software that does not have these disadvantages found in TRNSYS.

4 Search of Real Data and their Check with MATLAB/ Simulink

4.1 Irradiance Data

For searching appropriate solar irradiance data for PV systems it is necessary to decide which season will be considered, the location and the orientation of the modules.

Regarding the orientation of the modules, in order to most effectively use solar irradiation, a PV module is commonly aligned through its azimuth and tilt angles to achieve the greatest possible power production. There are different definitions and symbols to define these angles. Here it the DIN 5034-2 is used.

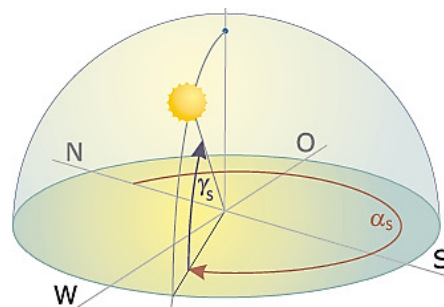


Figure 11: Azimuth angle (α_s) and tilt angle (γ_s) [13]

The azimuth angle (α_s) specifies how many degrees the surface of the module or collector diverges from the exact north-facing direction. The tilt angle (γ_s) specifies the divergence from the horizontal. The most common azimuth and tilt angles used for south or east-west orientated systems are resumed in the Table 4:

Table 4: Examples of current azimuth and tilt angles for south or east-west orientated PV systems [13]

| Angle \ Orientation | South | | East-west | | |
|---------------------|------------------------|------|-----------|------|-----|
| | Azimuth (α_s) | 180° | 90° | 270° | |
| Tilt (γ_s) | 30° | 15° | 20° | 25° | 30° |

The irradiation databases showed in the Table 5 have been considered:

Table 5: Irradiation databases and kind of data offered by each one

| Source \ Options | Type of data | Season | Orientation | Angle |
|---|-----------------|--------|-------------|-------|
| Hochschule Osnabrück | Real | Any | South | 30° |
| PV-GIS | Monthly average | Any | Any | Any |
| Typical Meteorological Year (TMY) Test Reference Years (TRY) | Average | Any | South | Any |

After this brief revision, the decision of using the PV-GIS database is made. The priority of this work is to compare the effects of using south and E-W oriented PV systems with different angles, and the mentioned source can provide the required data for this objective.

The data from the Hochschule Osnabrück are exclusively used in the section 4.1.1 in order to see the appearance of some real irradiance data. But from the section 4.1.2 onwards only data from PV-GIS are considered.

4.1.1 South

These data correspond to the irradiance obtained over the whole day on the 2013-07-01 by the south oriented equipment held on the roof of the AD building at the Hochschule Osnabrück (Germany). The results were obtained by the pyrometer with a plane inclination of 30° and plane orientation of 0° (south).

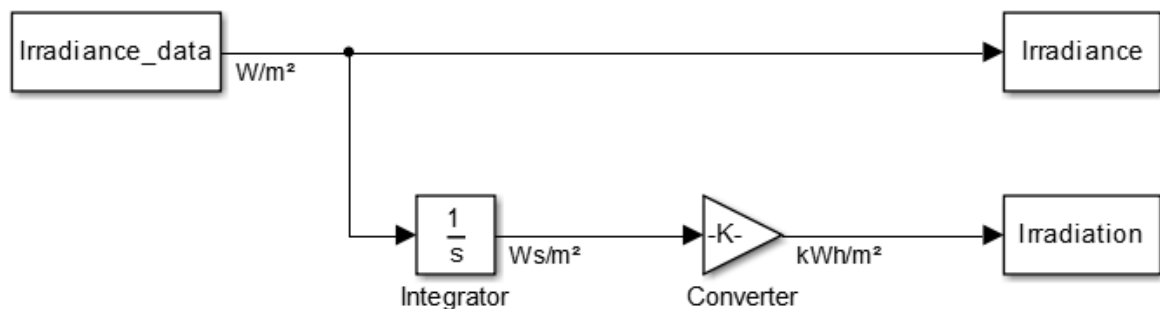


Figure 12: Model for representing the irradiance and the irradiation provided by the sun

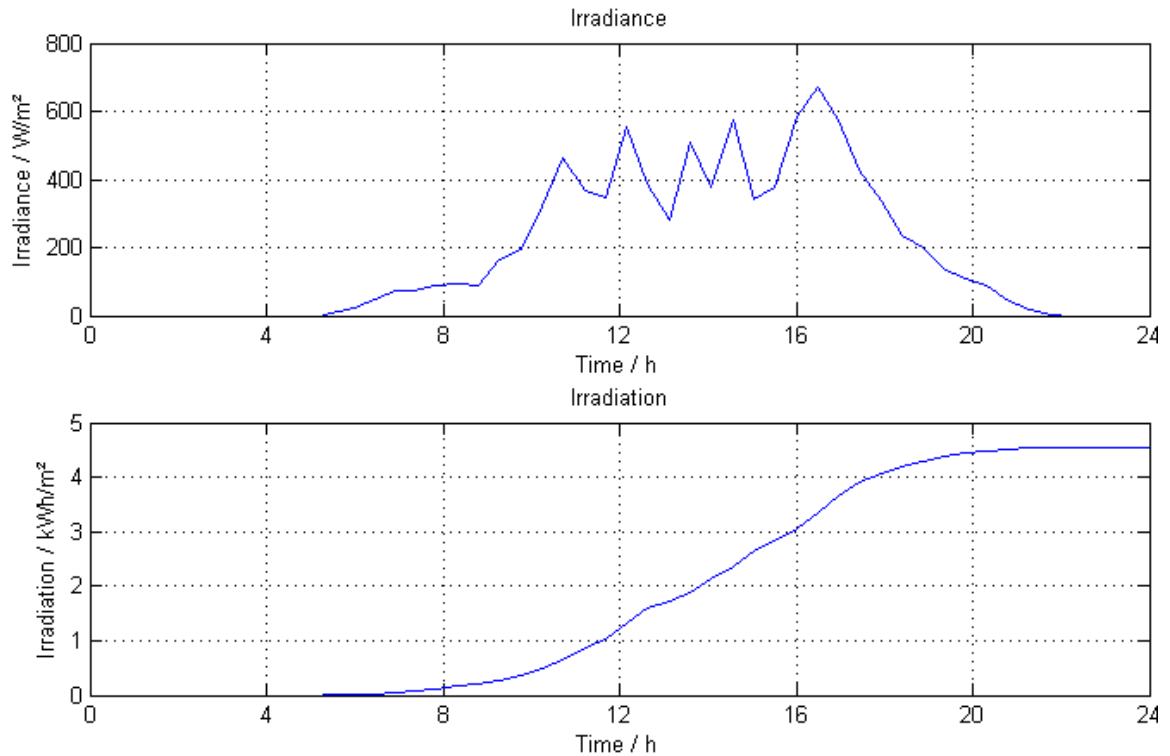


Figure 13: Irradiance and irradiation data over one day

In the Figure 13 it can be seen that real irradiance data shape irregular curves with sharp angles over the time.

4.1.2 East-west

The source for our east-west irradiance data is the PV-GIS solar radiation database provided by the European PV Geographical Information System [14]. The location selected is Osnabrück (Germany) and the results are the average irradiance over one day in July 2013 obtained by modules with a plane inclination of 15° and a plane orientation of 90° for the east and -90° for the west.

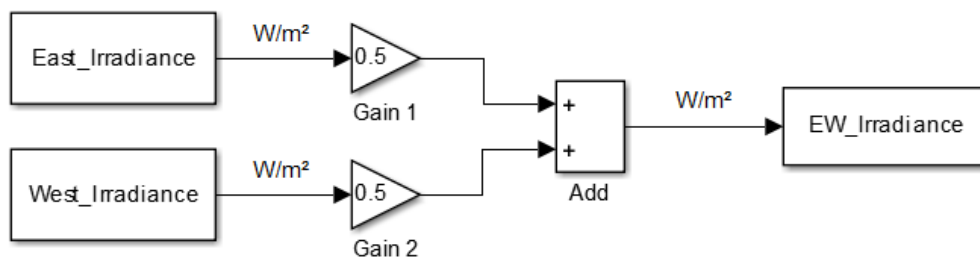


Figure 14: Model for representing east, west and E-W solar irradiance

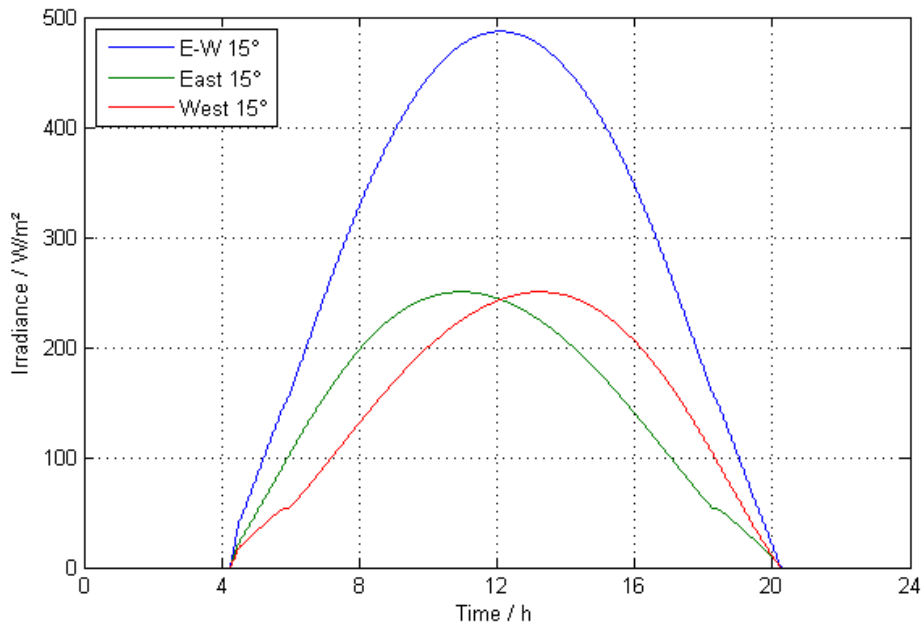


Figure 15: Average solar irradiance on east-west 15°, east 15° and west 15° PV systems over one day in July

In the Figure 15 it can be seen that average irradiance data shape regular curves with soft angles over the time.

4.1.3 Comparison of South and East-West

The Figure 16 shows the Simulink model built for running the daily irradiance and calculating its corresponding irradiation.

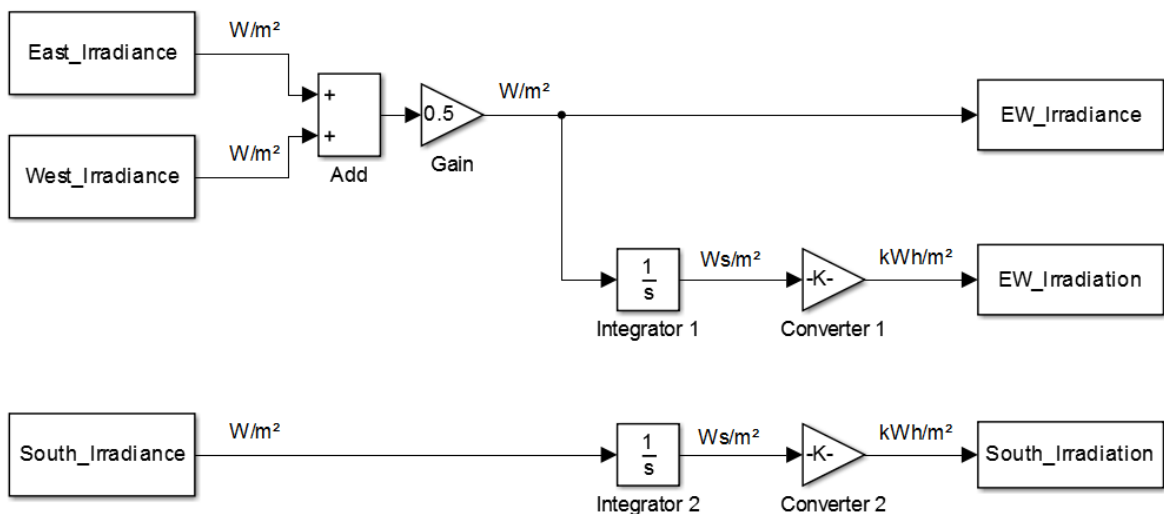


Figure 16: Model for representing south, east, west and E-W solar irradiance and irradiation

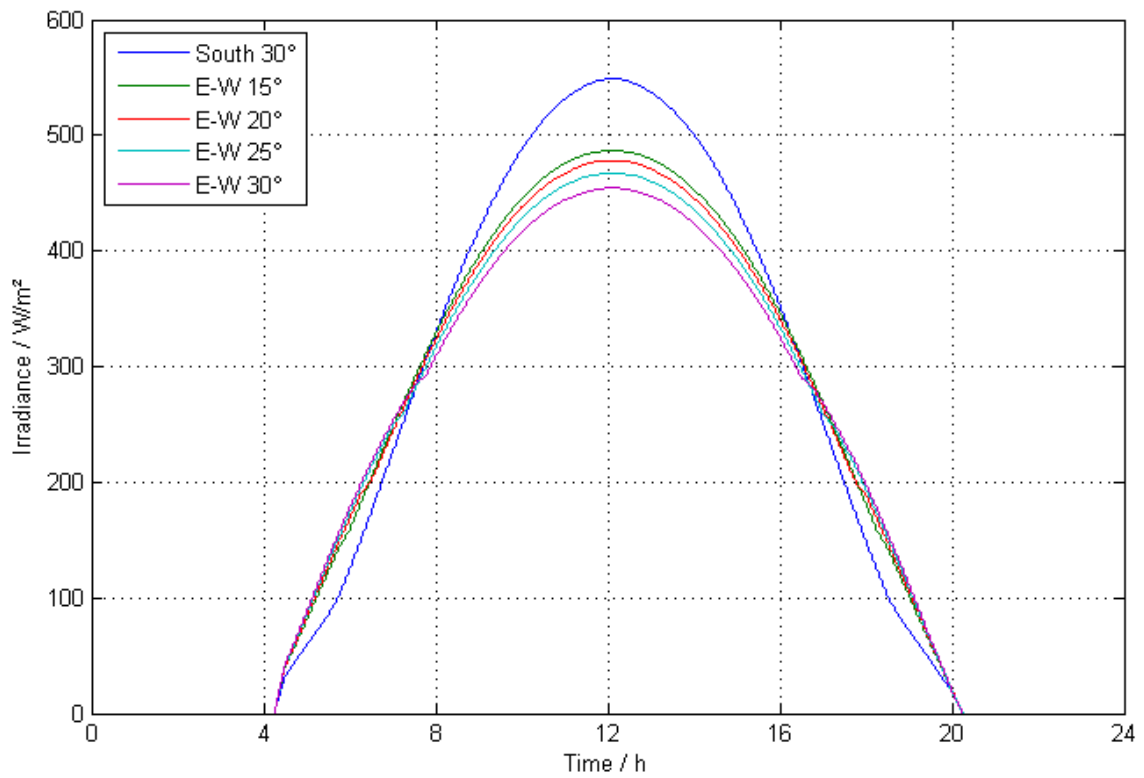
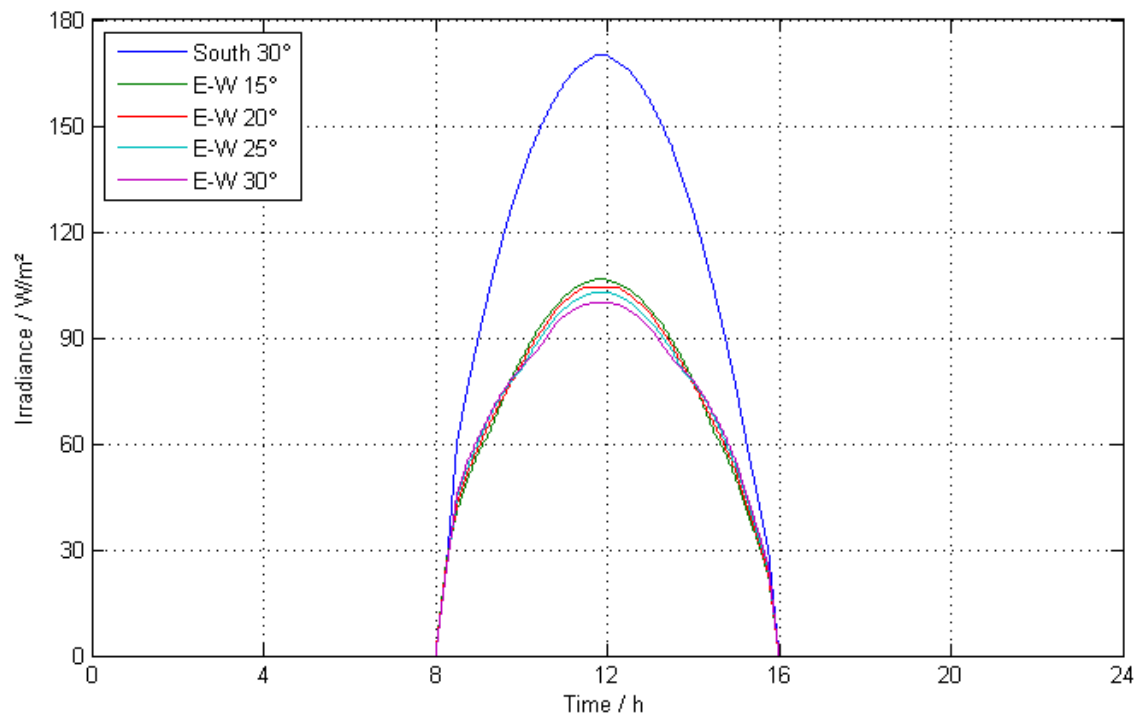


Figure 17: Average solar irradiance on south 30°, east-west 15°, 20°, 25° and 30° PV systems over one day in a) January and b) July

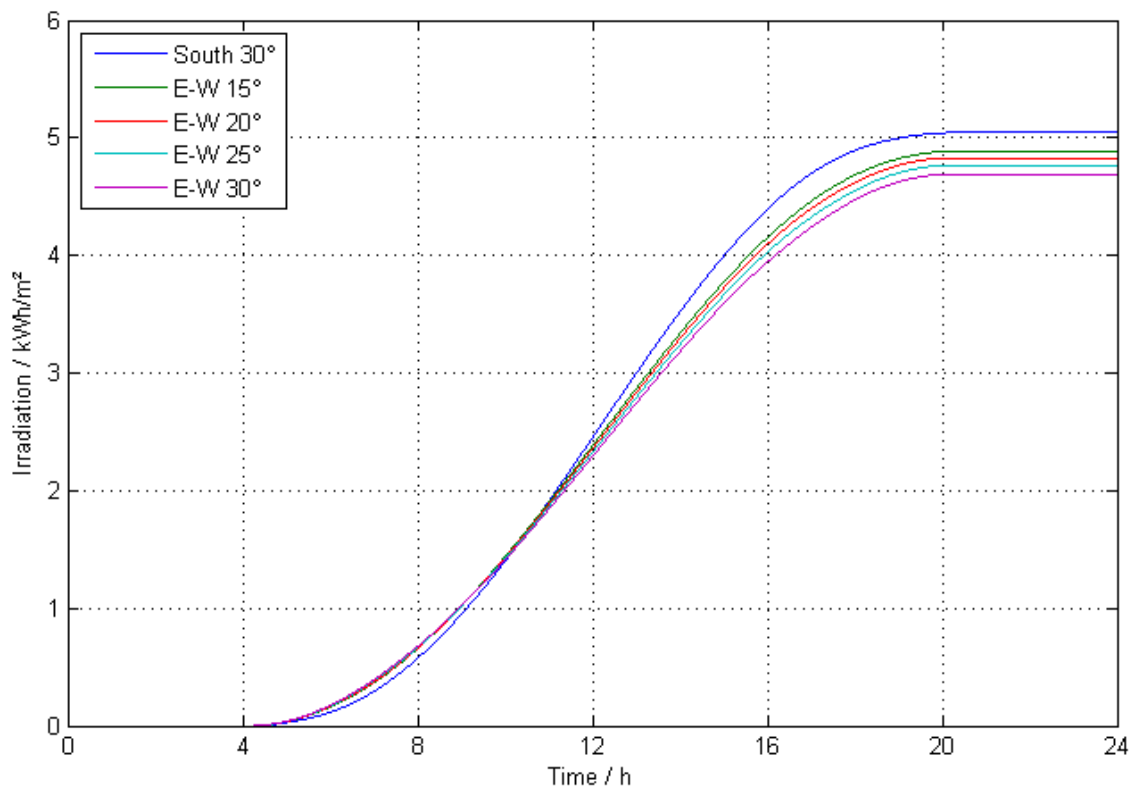
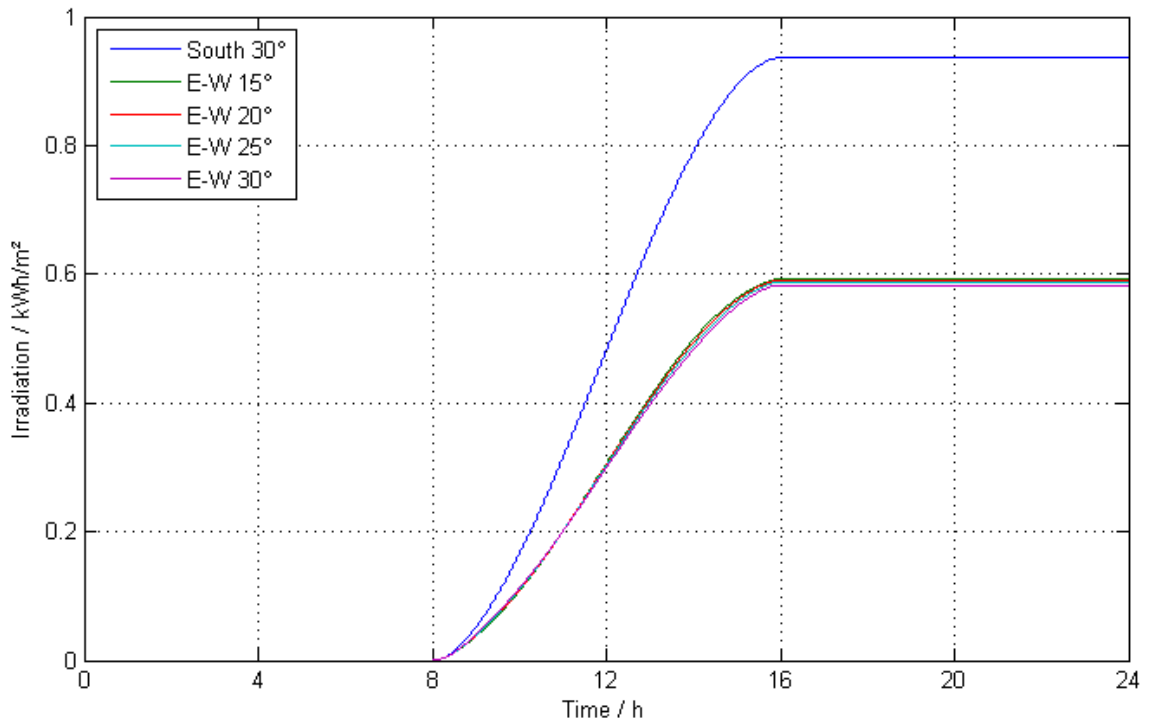


Figure 18: Irradiation incident on a south 30°, east-west 15°, 20°, 25° and 30° PV system over an average day in a) January and b) July

Some conclusions are deduced from the Figure 17 and Figure 18. Firstly, it can be seen that with a 30° tilted south orientation the irradiance has a higher peak in the midday and the total irradiation is also higher than that produced at any inclination with an E-W orientation. On the other hand, the E-W orientation shows that even though the total irradiation is lower, which means an economic disadvantage, the irradiance can be absorbed by the PV system during more hours over the day.

The second conclusion relates to the influence of the inclination on an E-W PV system. A higher tilt angle spreads more the yield, which means, the irradiance curve covers more hours over the day but on the other hand the total irradiation obtained is lower. The opposite phenomenon happens as the tilt angle gets lower.

Thirdly, comparing January to July, it is clear that these aspects mentioned above that difference south and E-W PV systems are more noticeable in January. For instance, for achieving the output power of a south system with a 15° tilted E-W system, it would be necessary to install 37% more modules in January and 11% in July.

4.2 Load profile of an Industry in Germany

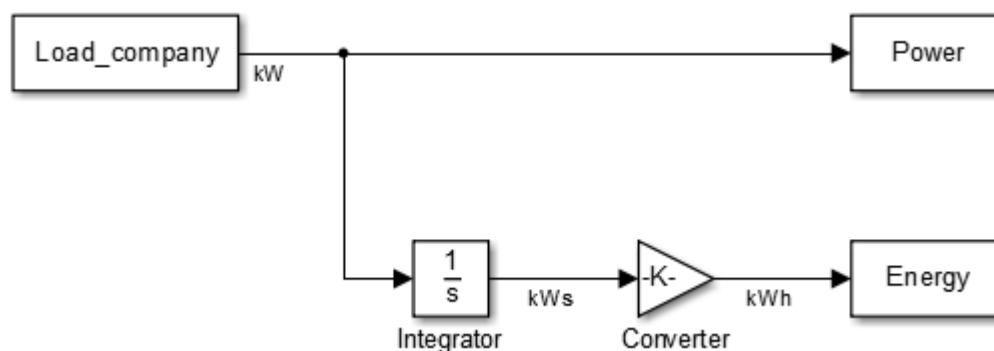


Figure 19: Model for representing the power and the energy demanded by a company

In the Figure 20 the load profile of the company is represented by a bar graphic because the demand is measured by the electricity company as the average power consumption for every 15 minutes.

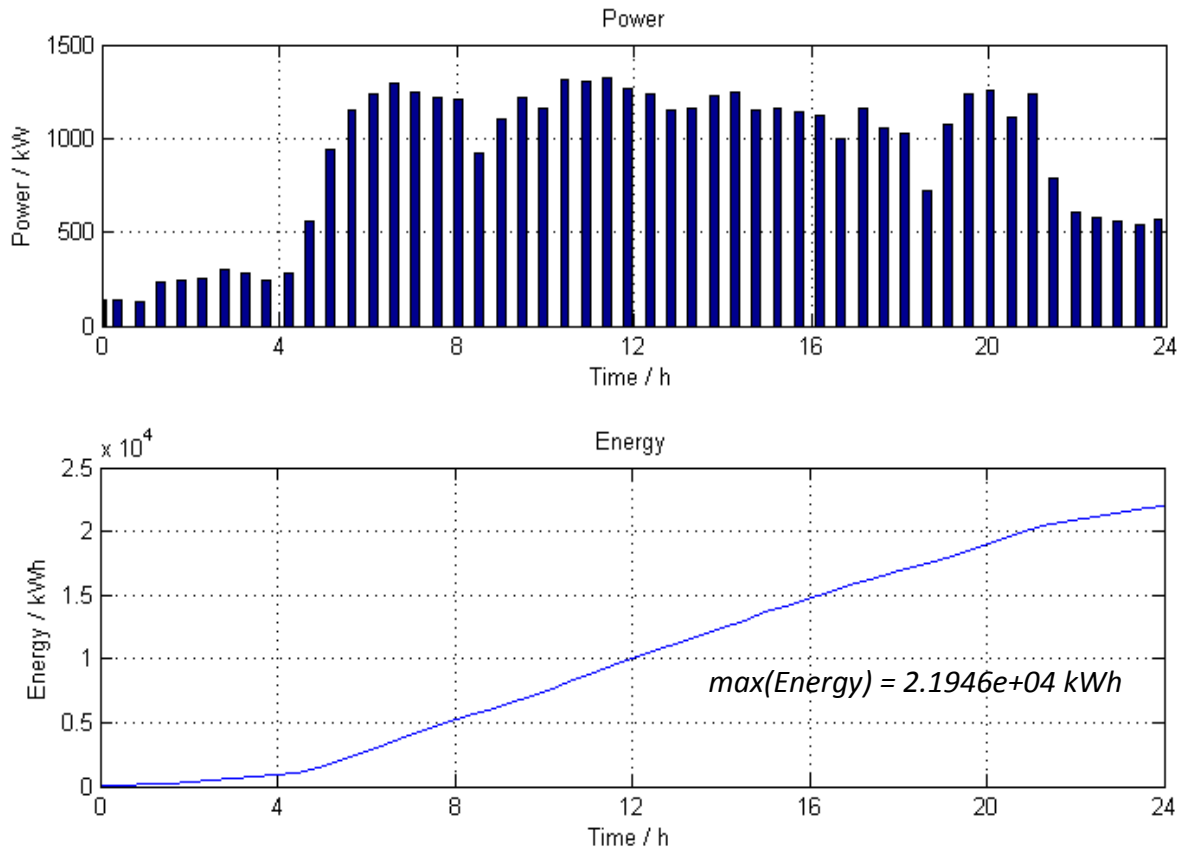


Figure 20: Power and energy consumed by a company each 15 minutes over a day

5 Simulation of the PV System Components by MATLAB/Simulink

In this chapter, the models and the simulation of each component of a grid-connected east-west PV system with a small storage capacity used by an industry are presented. The solar cell and the battery are already available in the Simulink library and they are analysed in the first place. Nevertheless, it is necessary to design and build models of the grid, the MPP tracker and the controller of the system and this task will be conducted in the second part of the present chapter.

5.1 Components Available

In this section, the different components already available in the library of MATLAB / Simulink are analysed in order to test if their performance is appropriate, by evaluating their main characteristic parameters and their performance as well. These components are the following:

In the first place the solar cell, many of which make a module, the joint of modules in series constitute a string and the assembly of various strings makes the base of a PV generator. This block is available in the SimElectronics package [9].

Secondly the battery: In this case, a lead-acid battery is presented, which is the most typical option for these installations. Its block is available in the SimPowerSystems package [10].

5.1.1 Solar Cell

A photovoltaic cell is a specialized semiconductor diode that converts light into direct current (DC). Its parameters depend essentially on sunlight irradiance and temperature.

Due to the low voltage of an individual solar cell (typically ca. 0.5 V), several cells are usually first connected in series and in parallel to make a photovoltaic module and to

obtain the desired voltage; the individual strings of modules are then connected in parallel to obtain photovoltaic arrays that allow the system to produce more current. The voltage and current produced at the terminals of a PV generator can feed a DC load or an inverter to produce AC current.

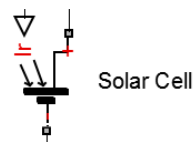
Solar panels are typically measured under standard test conditions (STC): 1000 W/m² solar irradiance, 25 °C for the PV module temperature and spectrum of air mass (AM) equal to 1.5.

5.1.1.1 Main Parameters

Here the main parameters of a solar cell are exposed, and also how they can be managed by the solar cell block from SimElectronics. The following description has been taken from [9].

The solar cell block represents a solar cell current source and it has the following ports:

- I_r Incident irradiance.
- + Positive electrical voltage.
- Negative electrical voltage



The block represents a single solar cell as a resistance R_s that is connected in series with a parallel combination of a current source, two exponential diodes and a parallel resistor R_p . Figure 21 shows the equivalent circuit diagram.

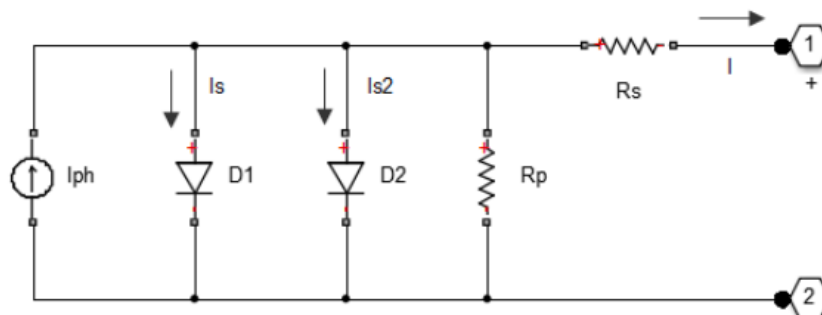


Figure 21: Equivalent circuit diagram of the solar cell block from the SimElectronics library

The output current is:
$$I = I_{ph} - I_s \cdot \left(e^{\frac{V+I \cdot R_s}{N \cdot V_t}} - 1 \right) - I_{s2} \cdot \left(e^{\frac{V+I \cdot R_s}{N_2 \cdot V_t}} - 1 \right) - \frac{V + I \cdot R_s}{R_p}$$

Where:
$$I_{ph} = I_{ph0} \cdot \frac{I_r}{I_{r0}}$$

With:

I_{ph} solar-induced current:

I_r irradiance in W/m² falling on the cell.

I_{ph0} measured solar-generated current for the irradiance I_{r0} .

I_s saturation current of the first diode.

I_{s2} saturation current of the second diode.

V_t thermal voltage, kT/q, where:

k Boltzmann constant.

T device simulation temperature parameter value.

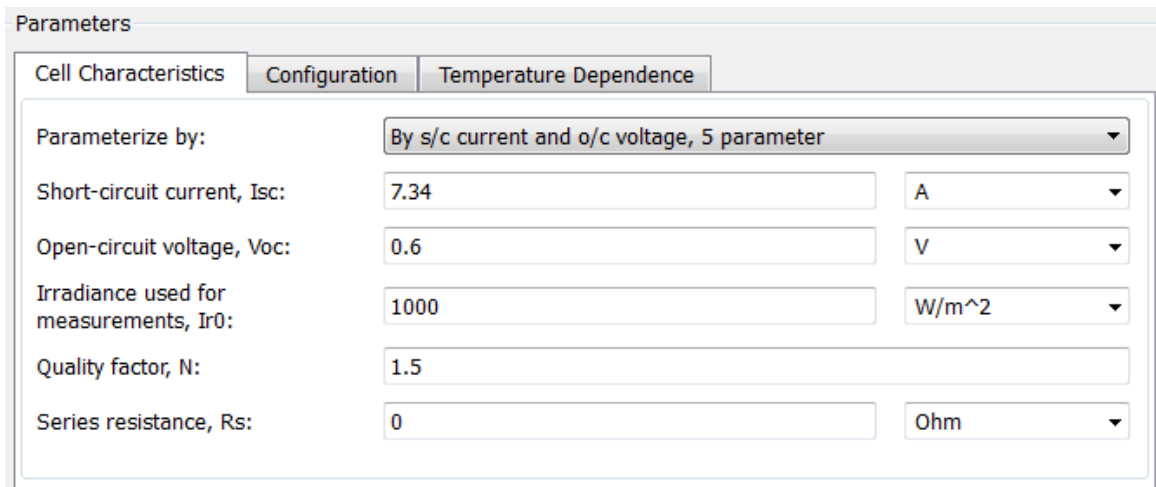
q elementary charge of an electron.

N quality factor (diode emission coefficient) of the first diode

N_2 quality factor (diode emission coefficient) of the second diode.

V voltage across the solar cell electrical ports.

The dialog boxes and parameters are the following:

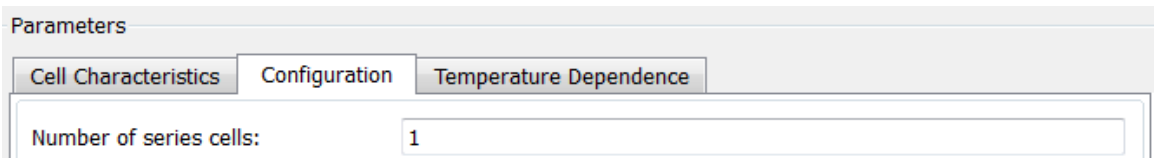


| Parameters | | |
|--|---|------------------------|
| Cell Characteristics | Configuration | Temperature Dependence |
| Parameterize by: | By s/c current and o/c voltage, 5 parameter | |
| Short-circuit current, Isc: | 7.34 | A |
| Open-circuit voltage, Voc: | 0.6 | V |
| Irradiance used for measurements, Ir0: | 1000 | W/m ² |
| Quality factor, N: | 1.5 | |
| Series resistance, Rs: | 0 | Ohm |

Figure 22: Main parameters table of the Solar Cell model

The following cell characteristics can be modified:

- *Parameterize by:* “By s/c current and o/c voltage, 5 parameter” - Provide I_{sc} and V_{oc} that the block converts to an equivalent circuit model of the solar cell.
- *Short-circuit current, I_{sc} :* the current that flows when you short-circuit the solar cell. The default value is 7.34 A.
- *Open-circuit voltage, V_{oc} :* the voltage across the solar cell when it is not connected. The default value is 0.6 V.
- *Irradiance used for measurements, I_{r0} :* the irradiance that produces a current of I_{sc} in the solar cell. The default value is 1000 W/m².
- *Quality factor, N :* the emission coefficient of the first diode. The default value is 1.5.
- *Series resistance, R_s :* the internal series resistance. The default value is 0 Ω .



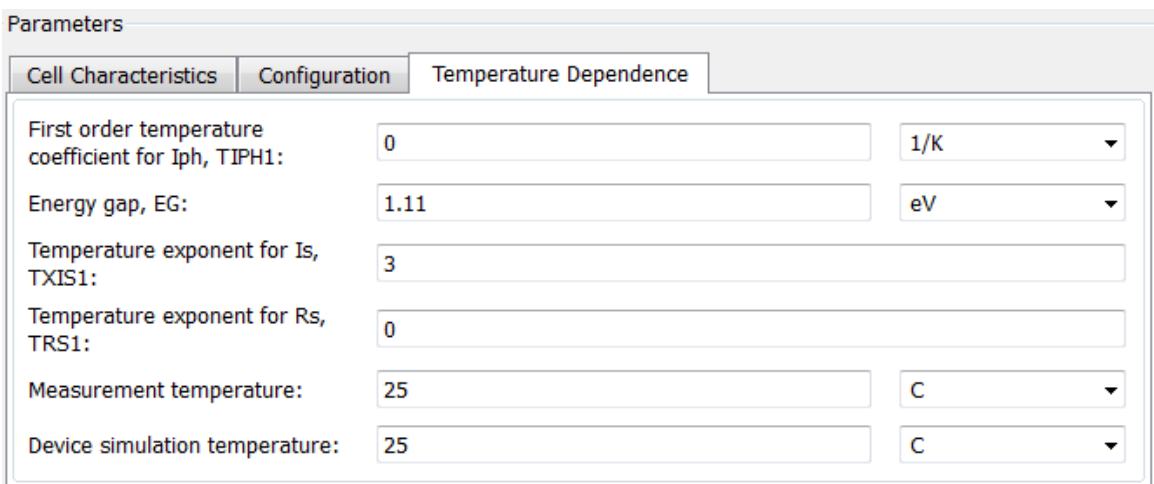
Parameters

Cell Characteristics Configuration Temperature Dependence

Number of series cells: 1

Figure 23: Configuration table of the Solar Cell model

By this window the number of cells in a series may be chosen. In this section only one solar cell is analysed.



Parameters

Cell Characteristics Configuration Temperature Dependence

First order temperature coefficient for I_{ph} , TIPH1: 0 1/K

Energy gap, EG: 1.11 eV

Temperature exponent for I_s , TXIS1: 3

Temperature exponent for R_s , TRS1: 0

Measurement temperature: 25 C

Device simulation temperature: 25 C

Figure 24: Temperature table of the Solar Cell model

Even though the model adjusts the block resistance and current parameters as a function of temperature, a remarkable drawback of this block is that these temperatures (both the

measured and the corresponding to the device) cannot be variable; they must be constant for the whole course of the simulation (see Figure 24) and therefore make our model much unrealistic. In a real device, the temperature variations have a remarkable influence on the internal resistance and consequently on the performance of the module.

5.1.1.2 I-U Characteristic Curve

- ***In theory***

Each PV module can be characterized by its performance curve (see Figure 25).

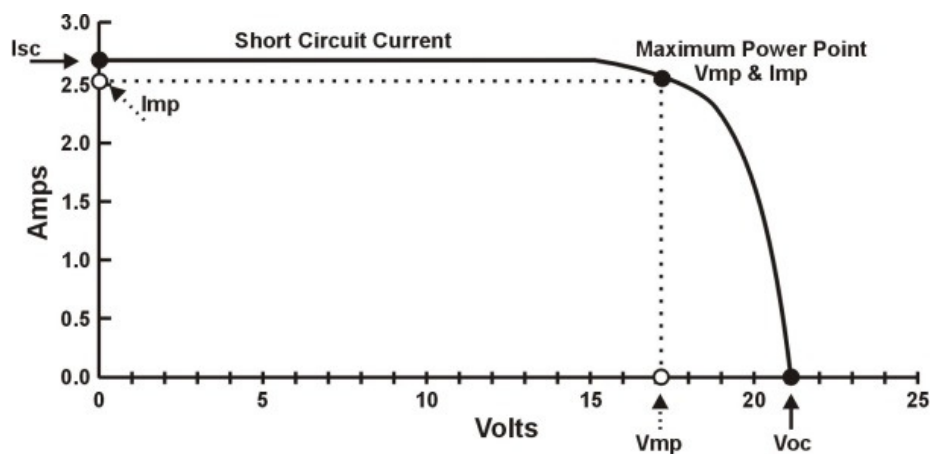


Figure 25: I-U characteristics of a PV module [7]

Three points on this curve are important in defining the performance of a PV module: the short-circuit current I_{sc} , the open-circuit voltage V_{oc} and the MPP, which is the point on the I-U curve at which the PV module works with maximum power output.

Figure 26 shows the current voltage (I-U) characteristics of a PV panel. These curves are nonlinear and crucially rely on the solar irradiance along with the temperature. When the irradiance increases, the current increases in a linear way and the maximum power point P_{mpp} increases as well. By temperature variations, the current changes less than the voltage and with the increasing temperature the power decreases.

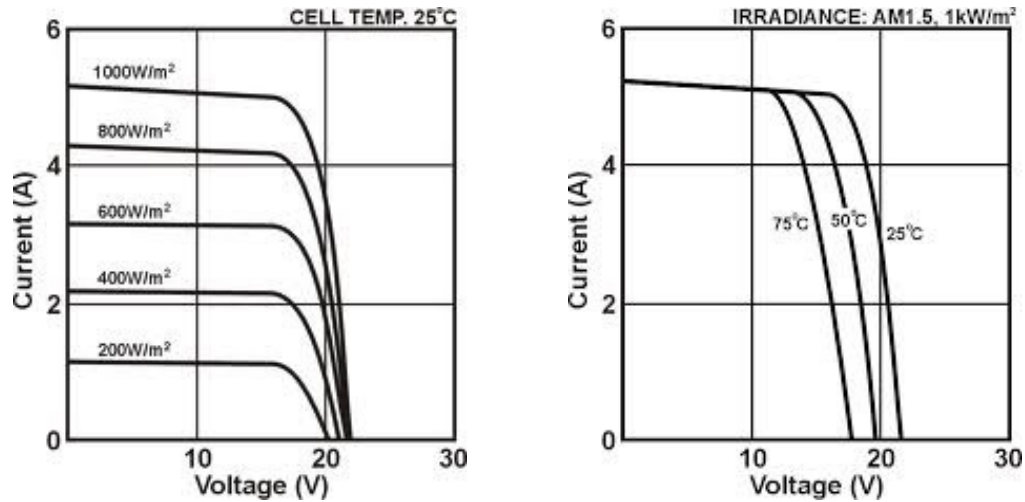


Figure 26: I-U characteristics of the PV. Left: At various irradiances, constant temperature of 25°C; Right: various temperatures, constant irradiance of 1 kW/m² [7]

- **In the simulation**

For checking the I-U characteristics, a model with a constant irradiance is simulated at STC. Its main components are the irradiance data selected, the solar cell block and a variable resistor in parallel. The initial value of the variable resistor is zero and it is increased gradually by the clock.

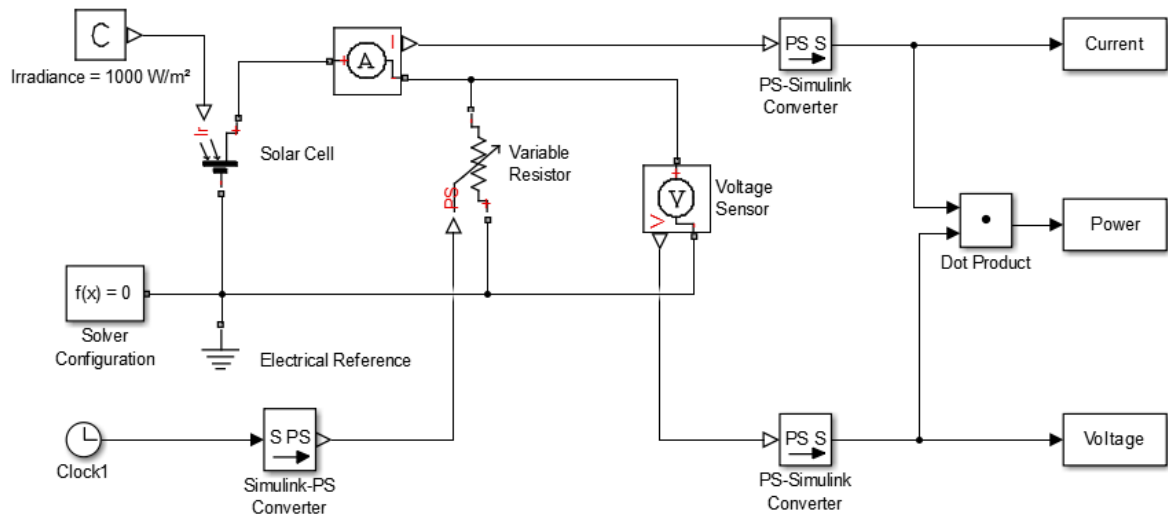


Figure 27: Model of a solar cell working at STC with a variable resistance in series

Figure 28 and Figure 29 show that the Simulink solar cell model in use here gives results that are in good coincidence with reality (see Figure 26).

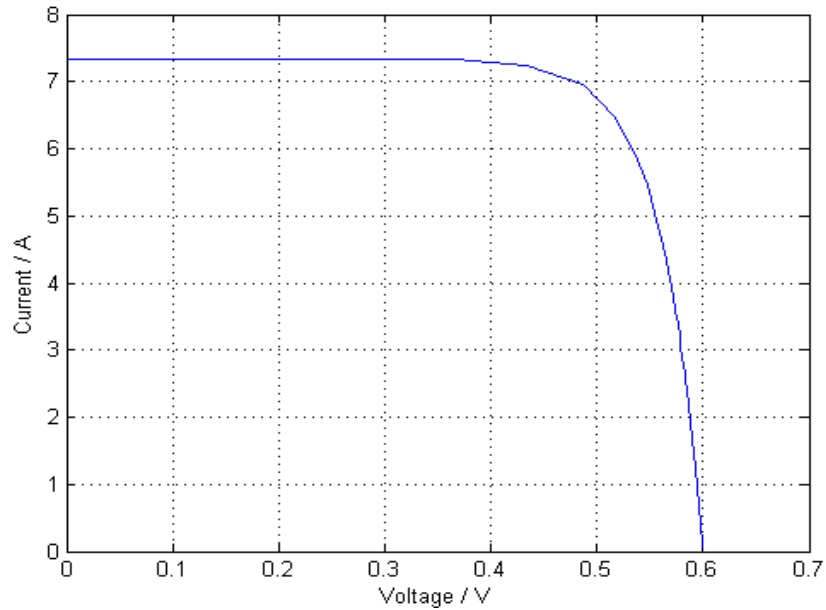


Figure 28: Simulated I-U characteristic curve of a solar cell working at STC

Analysing the results corresponding to a constant irradiance of 1000 W/m^2 shown in the Figure 28, it can be seen that the short-circuit current I_{sc} is 7.34 A, and the open-circuit voltage V_{oc} is 0.6 V, values that correspond to the parameters given in the Figure 22.

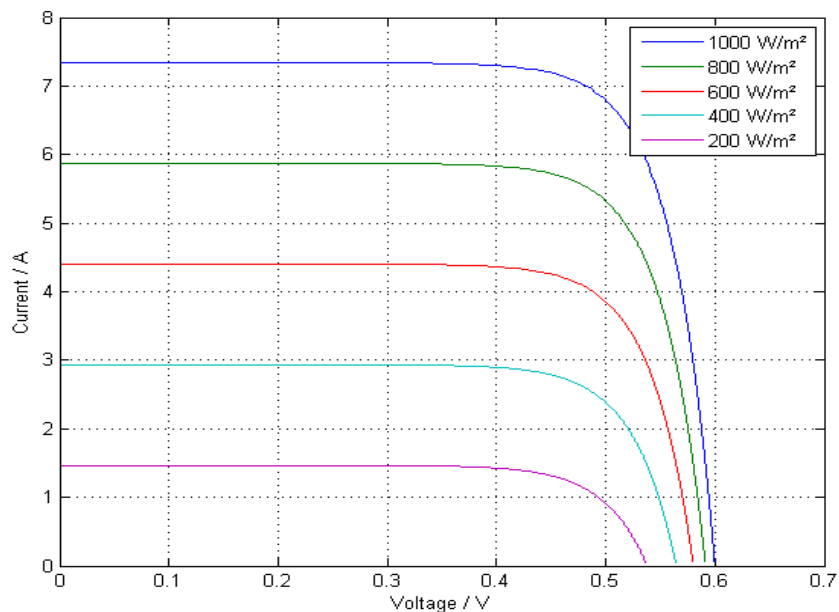


Figure 29: Simulated I-U characteristic curves of a solar cell at various irradiances, constant temperature of 25°C

As it can be seen in the Figure 29, as the irradiance decreases, both the I_{sc} and the V_{oc} are lower, although this effect is more remarkable in the I_{sc} .

5.1.1.3 MPP Characteristic Curve

- In theory**

A dynamic point exists on the I - U curve called the maximum power point (MPP), which depends on the solar cells used and on the operating conditions. This topic will be developed in more detail in the section 5.2.2.

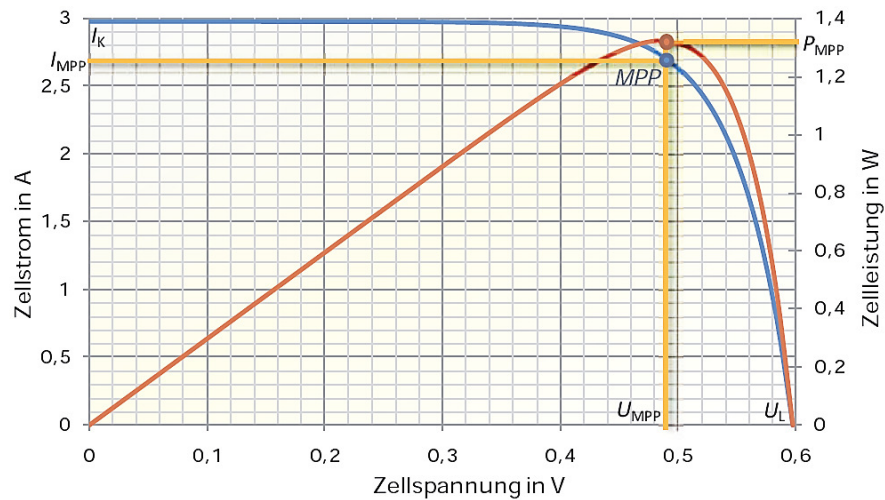


Figure 30: I - U and MPP curves of a solar cell at STC [13]

- In the simulation**

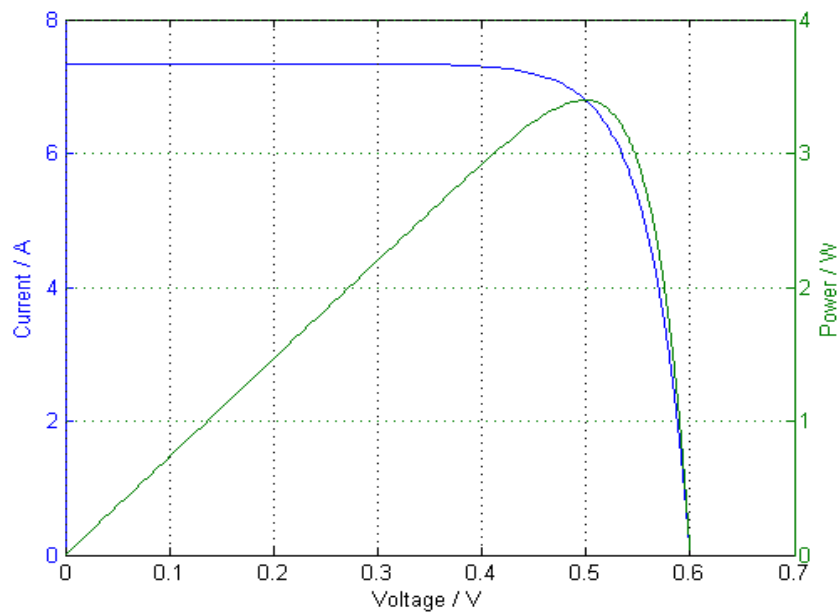


Figure 31: Simulated I - U and MPP curves of a solar cell at STC

When comparing the curves from the Figure 30 and Figure 31 it is observed that the shapes of the theoretical and simulated $I-U$ and MPP curves are very similar although the parameters have unequal values because they correspond to different solar cells.

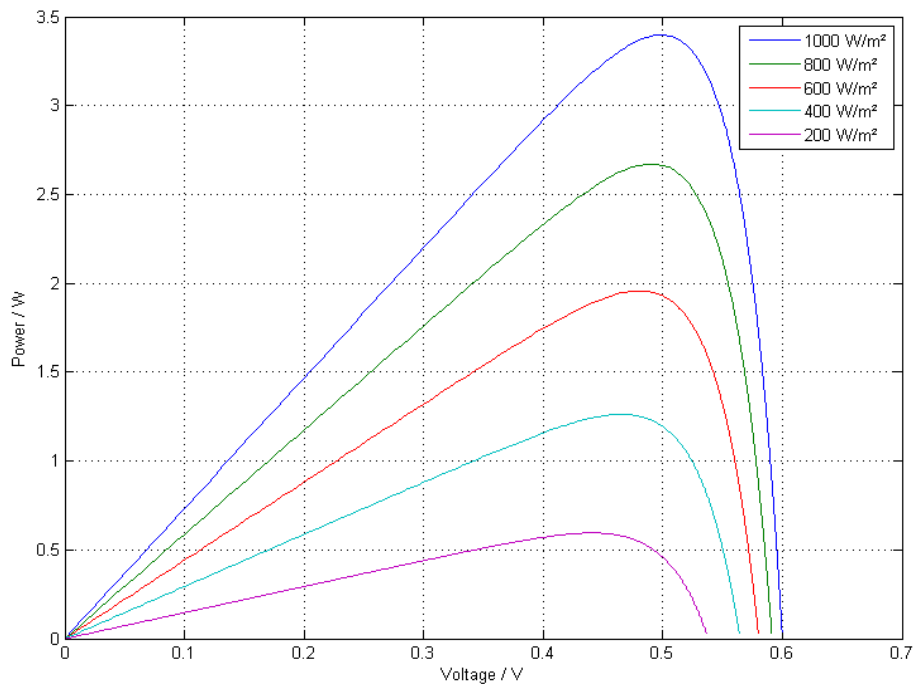
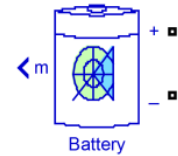


Figure 32: Simulated MPP curves of a solar cell at various irradiances, constant temperature of 25°C

The results of the Figure 32 show that as the irradiance decreases, the MPP gets gradually lower and they are similar to the operation curves from a real solar cell.

5.1.2 Lead-Acid Battery

Typically, the power generated by the solar panels charges a lead-acid battery although many other types are used.



5.1.2.1 Main Parameters

Here the main parameters from a lead-acid battery are exposed and the way they can be managed by the battery block from SimPowerSystems is shown. The following description has been taken from [10].

The battery block implements a generic dynamic model parameterized to represent the most popular types of rechargeable batteries. The equivalent circuit of the battery is shown in the *Figure 33*.

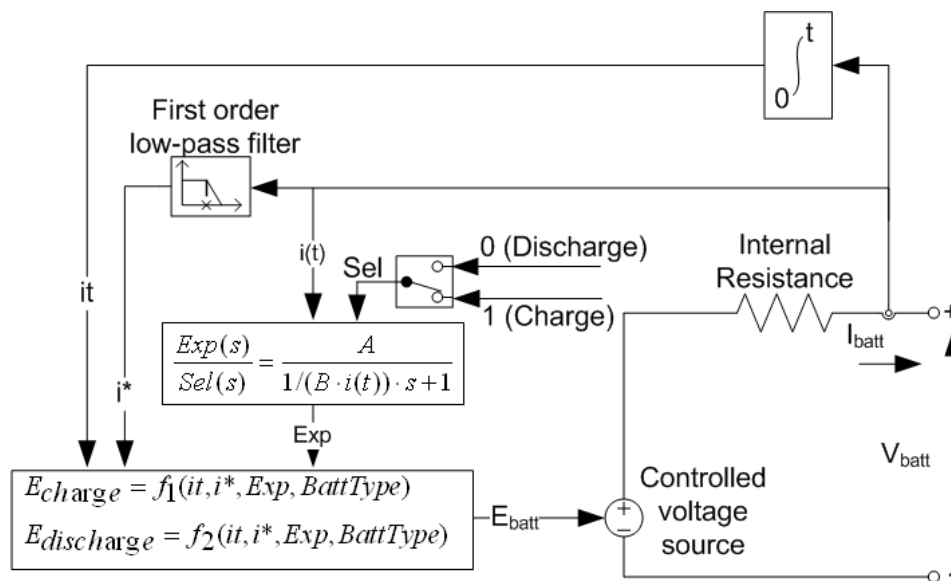


Figure 33: Equivalent circuit diagram of the battery block from SimPowerSystems

The discharge and charge equations for a lead-acid battery model are the following:

Discharge model ($i^* > 0$)

$$f_1(it, i^*, i, Exp) = E_0 - K \cdot \frac{C}{C - it} \cdot (i^* - it) + \mathcal{L}^{-1} \left(\frac{Exp(s)}{Sel(s)} \cdot 0 \right)$$

Charge Model ($i^* < 0$)

$$f_2(i, i^*, i, Exp) = E_0 - K \cdot \frac{C}{it + 0.1C} \cdot i^* - K \cdot \frac{C}{C - it} \cdot it + \mathcal{L}^{-1} \left(\frac{Exp(s)}{Sel(s)} \cdot \frac{1}{s} \right)$$

With:

E_{Batt} Nonlinear voltage (V)

E_0 Constant voltage (V)

$Exp(s)$ Exponential zone dynamics (V); this transfer function represents the hysteresis phenomenon during charge and discharge cycles

$Sel(s)$ Represents the battery mode. $Sel(s) = 0/1$ during battery dis/charge

K Polarization constant (Ah^{-1}) or Polarization resistance (Ohms)

i^* Low frequency current dynamics (A)

i Battery current (A)

it Extracted capacity (Ah)

C Maximum battery capacity (Ah)

A Exponential voltage (V)

B Exponential capacity (Ah^{-1})

\mathcal{L} Laplace transform

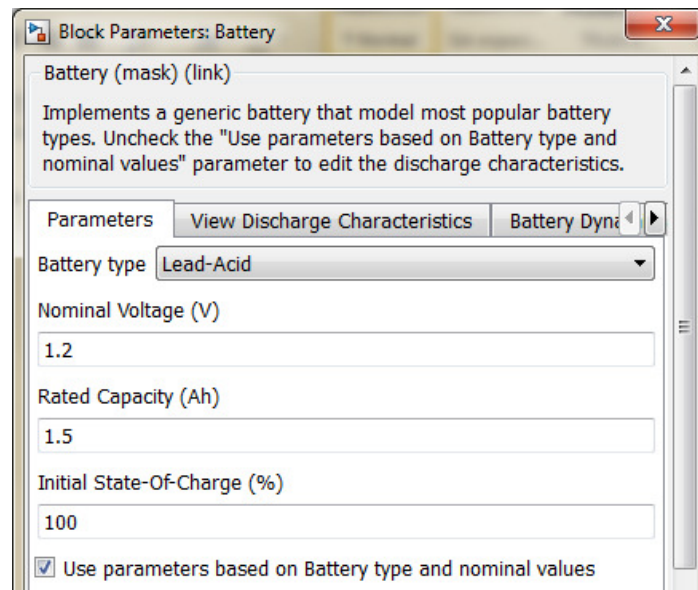


Figure 34: Dialog box and parameters of the battery model from SimPowerSystems

- Nominal Voltage (V_{nom} , V): represents the end of the linear zone of the discharge. After reaching this value the voltage decreases abruptly.
- Rated Capacity (C_n , Ah): minimum effective capacity of the battery. The effective or usable capacity is the amount of electricity released by a fully-charged battery during a complete discharge with a given current, voltage and temperature. The subscript n

represents the duration (in hours) of this discharge fixed by international standards. The charge or discharge current is often written in reference to its capacity. For instance, for a current $I = C/5$ for a battery whose capacity is $C = C_{10} = 15 \text{ Ah}$, this denotes a current of $C_{10}/5 = 15 \text{ Ah} / 5 \text{ h} = 3 \text{ A}$. For rapid discharges, one might speak of a 2C discharge [2]. Nevertheless, this charge / discharge current parameter is set as a default value based on the battery type and nominal values in this report.

- Initial State-Of-Charge (SOC, %): 100% indicates a fully charged battery and 0% indicates an empty battery.

5.1.2.2 Charge with Constant Current

There are different charging techniques for lead-acid batteries, but here the ΔV charging method is shown, which means charging at recommended constant current until the cell reaches a peak voltage.

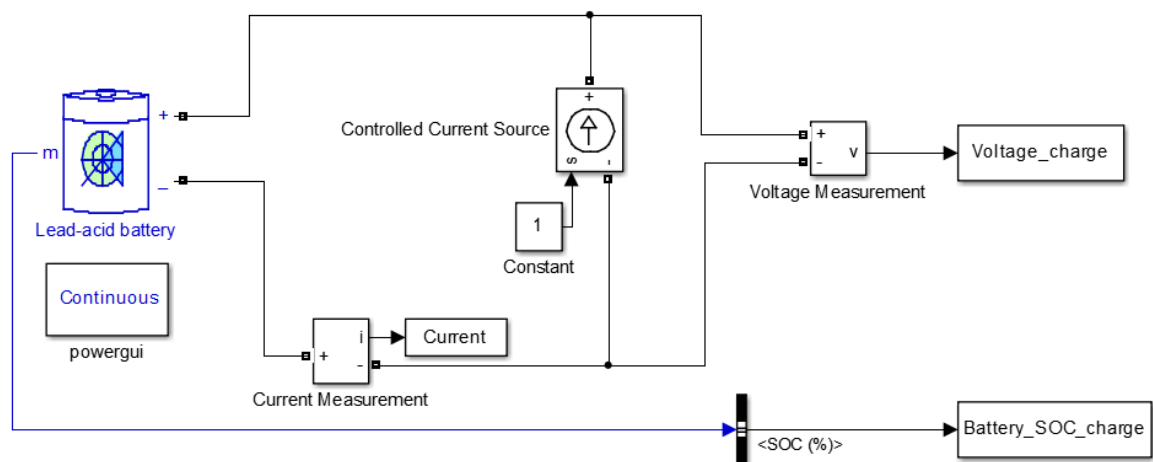


Figure 35: Model of a lead-acid battery charged with constant current

As the battery is being charged at constant current, the voltage remains near its nominal value (1.2 V in the example) and rises abruptly to a peak when the battery is almost fully charged. This voltage rising, remarked in the Figure 36 with a red circle, starts when the cell enters the overcharge danger zone. From that instant, the temperature begins to rise rapidly since the chemical changes are complete and the excess of electrical energy is converted into heat. This point can therefore be detected by the increase of voltage and used to identify the peak charge and to cut off the charger when the battery has reached its full charge.

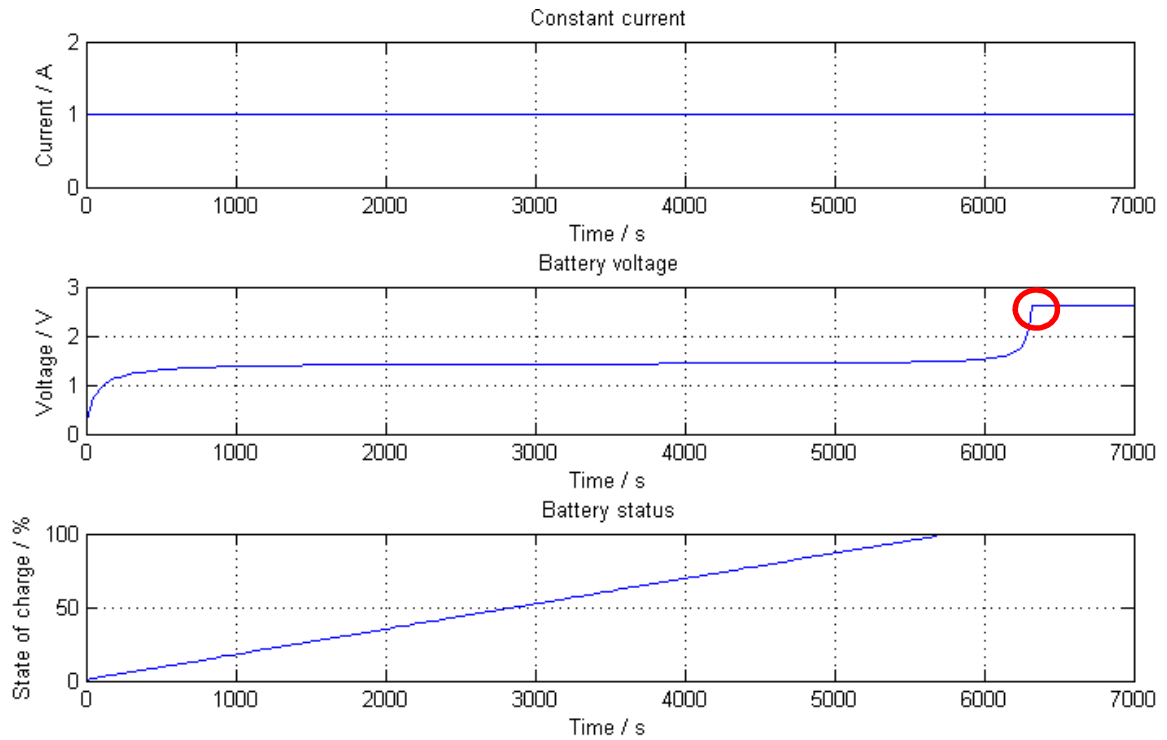


Figure 36: Simulation of the I , U and SOC over time of a lead-acid battery being charged with constant current

5.1.2.3 Discharge

Figure 37 shows the discharging model of a battery by a resistance in parallel. The voltage and the SOC are measured over the simulation.

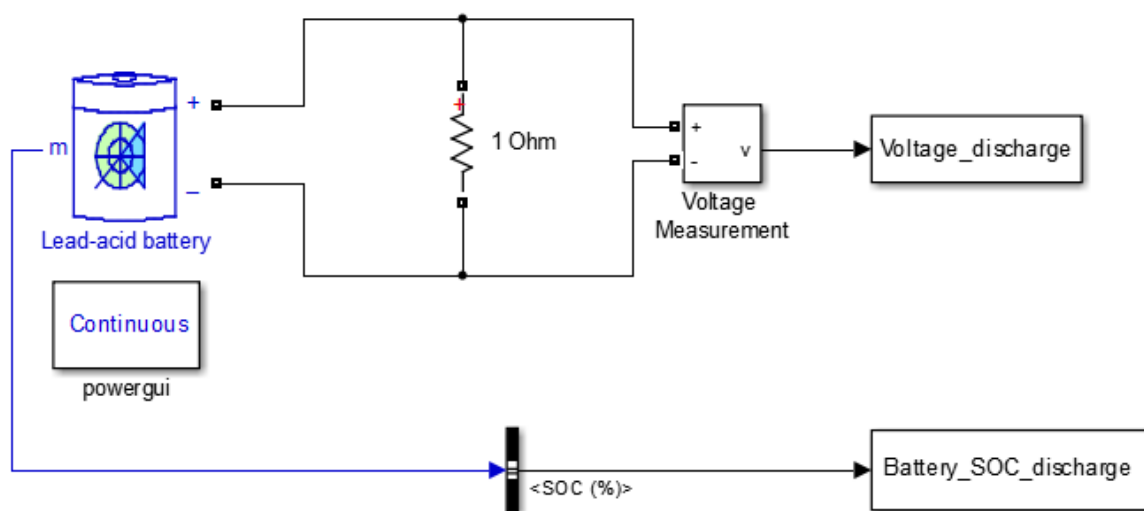


Figure 37: Model of a lead-acid battery discharge

Figure 38 shows the voltage and the SOC of the battery being discharged along the time. As it occurs theoretically, it proves that the lead-acid cells from this model have a fairly constant 1.3 V voltage, which drops below 1.1 V when they are nearly discharged [5].

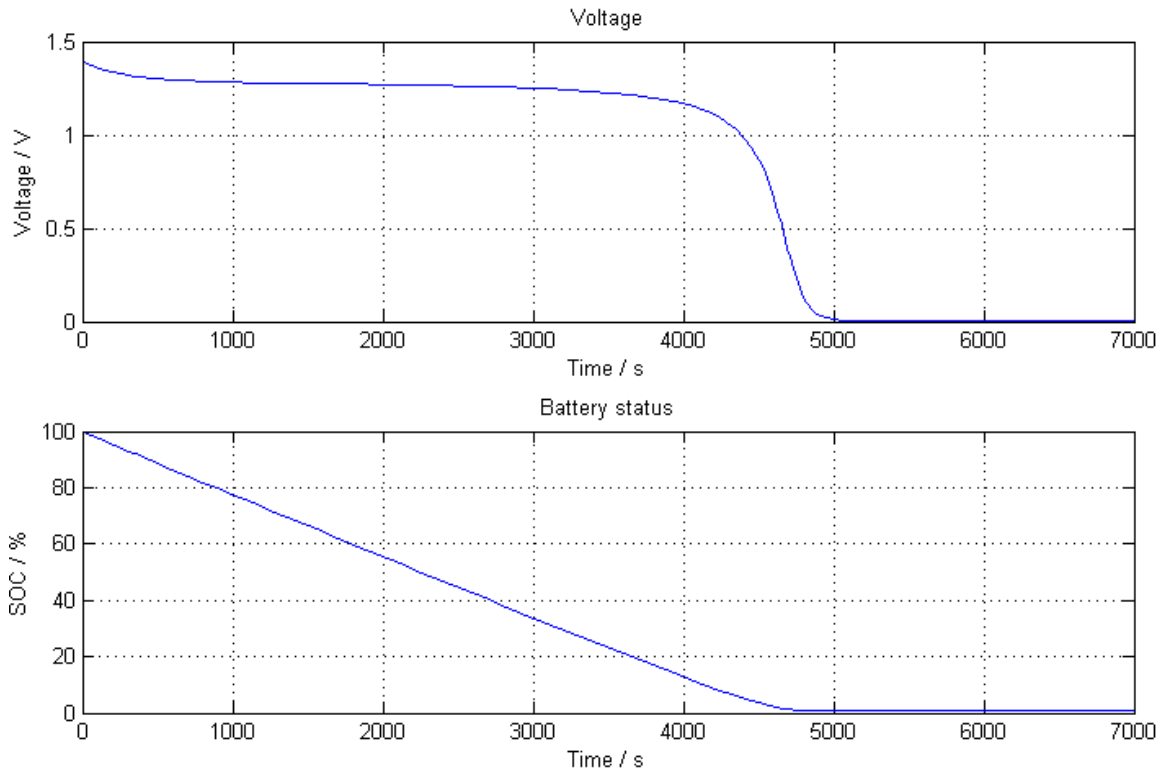


Figure 38: U and SOC along the time of a lead-acid battery being discharged

5.1.2.4 Hysteresis Effect

For a given state of charge, the open circuit cell voltage depends on whether this state was reached during the charging or discharging cycle and this leads to a hysteresis effect. The diagram from Figure 39 shows this effect observed in a typical a typical charge / discharge of a lead-acid battery.

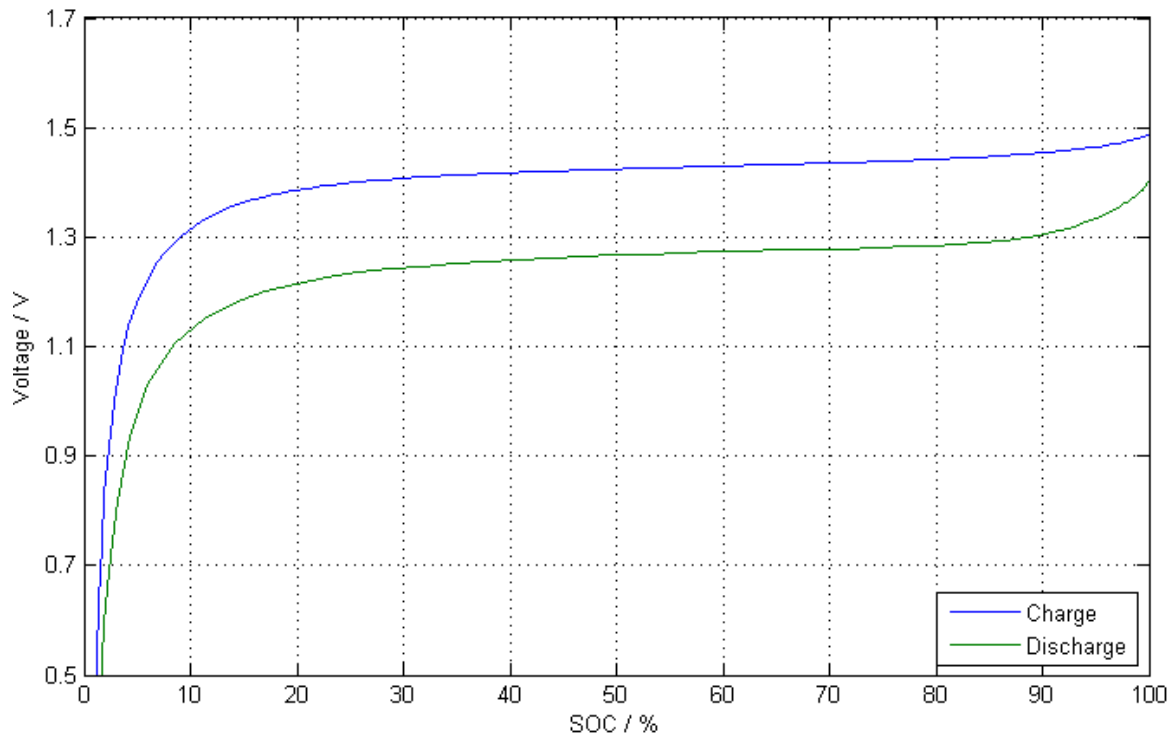


Figure 39: Simulated hysteresis effect in a lead-acid battery charge / discharge characteristic curves

After analysing the simulation results from both the solar cell and the battery models and comparing them to the theoretical ones, it is concluded that the correspondence is satisfactory excluding the fact that the simulation temperature for the solar cell must be constant, which is an important drawback.

5.2 Components not Available: Objective, Design and Model Limitations

5.2.1 Grid

In this section the grid functions within the PV system with a battery are described, but firstly it is necessary to bear in mind some specific characteristics of the electricity supply costs in Germany.

We should be aware that the consumption is measured by the electricity company each quarter of an hour and calculated as the average power consumed each 15 minutes. For the peak consumption power recorded in the particular 15 minutes of maximum consumption, the company must pay a power tariff for the whole following year. Hence, the company intends to keep its maximum consumption low, i.e. in shaving the peaks in Figure 40. The peak consumption price is actually 58 €/Kw [17]. That is the reason why it is so important to avoid these load peaks with the help of the PV panels and/ or the battery.

From this point the different grid functions are exposed and for this purpose some new variables are introduced here to the grid power depending on its dimensions and functions, just to make this explanation as clear as possible.

At the beginning it is necessary to set an arbitrary grid power threshold which will allow to distinguish between the base of the load profile and its peaks and its value must be constant for the whole year. This border is called *grid threshold* and it represents the power that will cover the base of the demand. It must be defined by bearing in mind the characteristics of the load profile from the specific consumer considered, the characteristics of the PV system and specifications of battery that is likely to be used in the system. In practice, this threshold will be shifted up and down for each particular simulation in order to find an optimum level which makes sure that the peaks will be covered even in the worst conditions, which means, with zero solar irradiance. In the example of Figure 40, the load profile reaches its top with approximately 1300 kW and the *grid threshold* has been arbitrarily set to 1000 kW (see shaded area). Some simple steps will be given in the section 6.1.3 for the *grid threshold* choice.

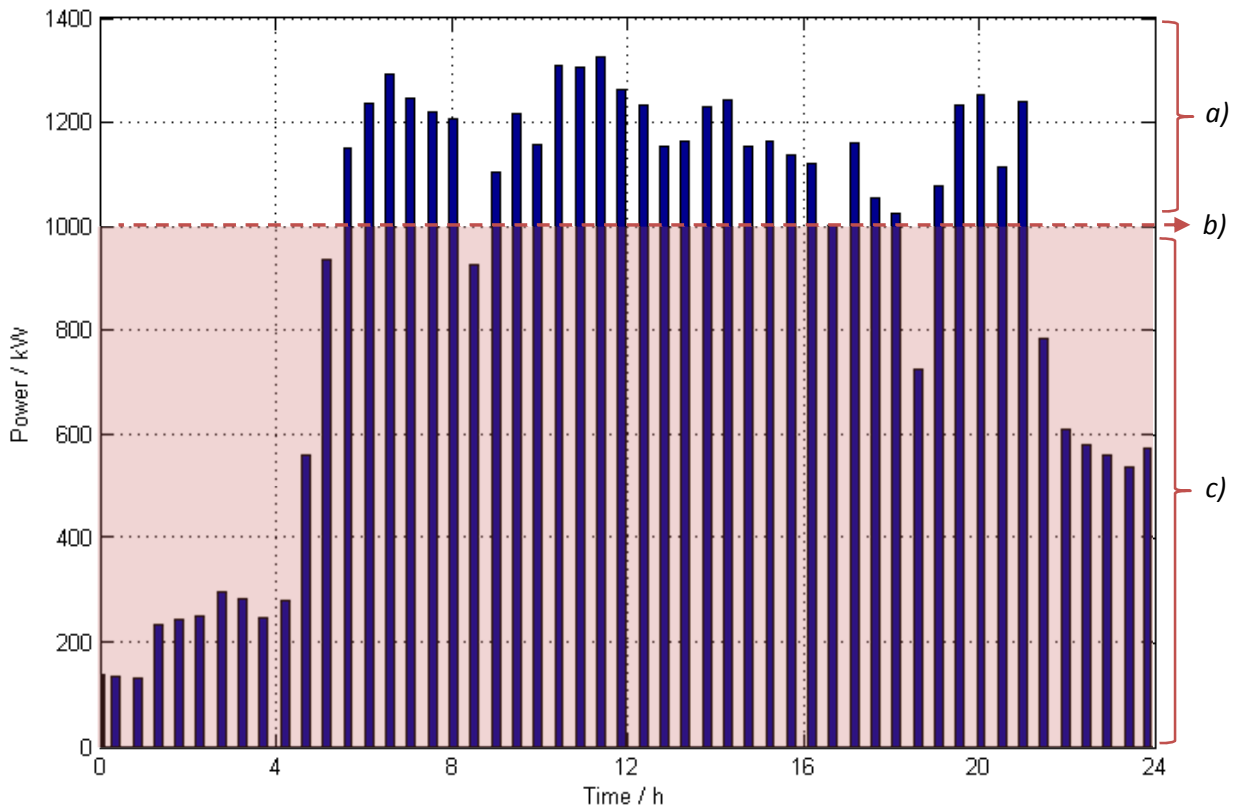


Figure 40: Load profile of an industry over one day and its grid threshold power defined;

- a) Load peaks: if possible they are firstly covered by the PV power, if not then by the battery discharge and all the rest by the grid;
- b) Grid threshold power: defined to cover the base of the demand, depending on the specific load profile curve and the kind of battery that is likely to be used for the system;
- c) Base of the demand: covered by the grid

In the first place, the grid must supply the necessary power for covering the base of the load profile, which means, all the demand except the peaks. This will be modeled by a power source which will supply the power required for covering the demand which is not covered by the PV system yet, as long its value is lower or equal to the *grid threshold*. This power is called *grid load*.

Secondly, it must be known that the battery must be generally full in order to cover the demand peaks and the role of the PV system is mostly to reduce the electricity consumption from the grid. If the result of the load minus the generated PV power is lower than the *grid threshold* defined previously, then the grid provides power to the



battery (if possible) besides to the load. It is cheaper to charge the battery by the grid while the load is under the *grid threshold* in order to prevent the next load peaks than using directly the grid power for covering these peaks instantaneously, because as explained before, then fixed costs of the electricity bill will be higher. Thus, the total power injected by the grid for charging the battery is called *grid battery supply*. It represents the power from the grid that charges the battery, without exceeding the *grid threshold*, after having already covered the whole demand. In practice, it is the value that results after subtracting to the *grid threshold* the *load* minus the *PV power* and will never exceed the maximum charge power bearable by the battery selected.

The addition of both *grid load* (power supplied to the load) and *grid battery supply* (power injected to the battery) must be equal or less than the *grid threshold* at every moment.

Finally, if firstly the PV system and secondly the battery cannot fulfil their peaks covering task, the grid must assure the complete supply by delivering what will be named as *grid exceeding threshold*.

In our Simulink model of the whole system the operation of the grid is carried out by two controllers and the grid subsystem will not affect the simulation. The aim of the components that are found within the grid model is sending to the workspace the variables that contain the fractions of the power supplied by the grid for fulfilling different tasks: cover the base of the load (*grid load*), charge the battery (*grid battery supply*) and deliver power that exceeds the threshold for covering the load peaks (*grid exceeding threshold*). The sum of these three variables is the total power provided by the grid (*power supplied by the grid*). The model from the grid behavior described above calculates these parameters as shown in the Figure 41.

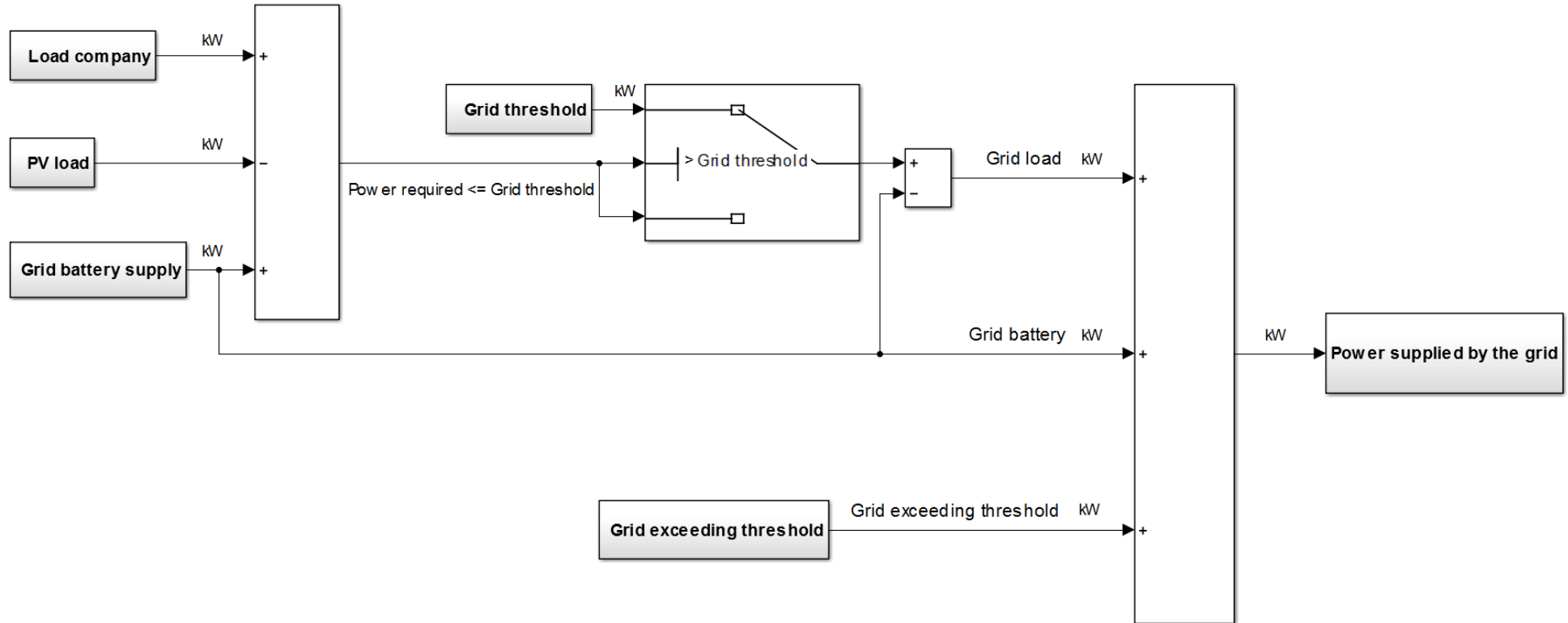


Figure 41: Model of a grid connected to a PV system with a battery

5.2.2 MPP tracker

The concept of MPPT (Maximum Power Point Tracking) has been already introduced in the section 5.1.1.3 (analyzing the performance of the solar cell model), but a deeper analysis is taken in this part. Next the design of an MPP tracker is presented and its simulation connected with a PV system. After that, there is an analysis of the results and a discussion about the limitations of this model.

5.2.2.1 Objective

The MPPT is an additional function made by the inverters of a PV system. The efficiency of a solar cell and therefore its maximum output power depends strongly on the irradiation, the device temperature and its total internal resistance. It has a non-linear dependence which can be analyzed based on the I-U characteristic curve of a solar cell (see Figure 42).

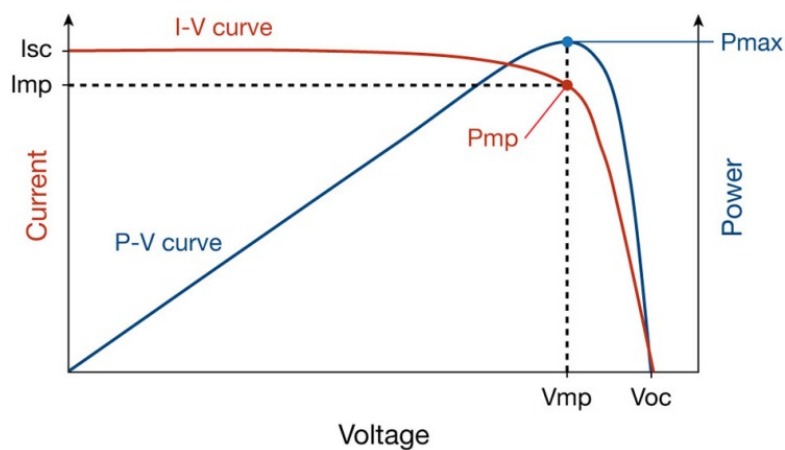


Figure 42: I-U and P-U curves with the MPP at STC

The location of the MPP is dynamic and unknown, and for that reason there are calculation models and search algorithm methods to sustain the PV operation at this point. Therefore, it is the purpose of the MPP controller to sample the output of the cells and apply the optimum resistance for the entire PV system to operate at maximum power for any given environmental conditions at every instant.

Since our solar cell model cannot be simulated with variable temperatures (see section 5.1.1.a), only irradiance variations will be considered for the design of the MPPT.

5.2.2.2 Design

For designing the MPPT, firstly a model of a solar cell is simulated with a time varying resistor in parallel and a constant irradiance of 1000 W/m^2 as input.

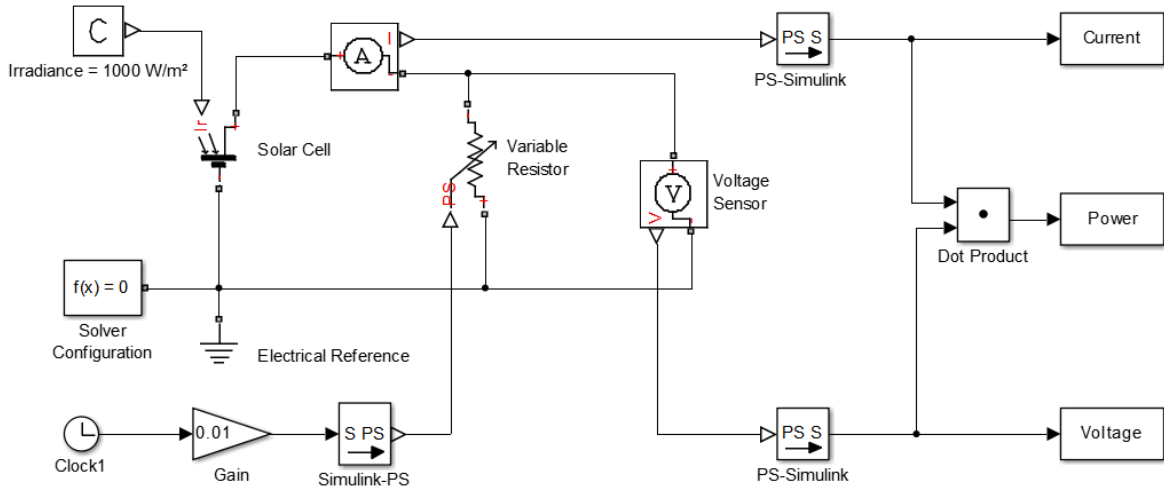


Figure 43: Model of a solar cell working at STC with a variable resistance in parallel

The aim is to discover, by analyzing its MPP curve, what is the optimum resistance for achieving maximum power with this particular irradiance.

After a 100 second time simulation of the model from the Figure 43, the graphs from Figure 44 are drawn.

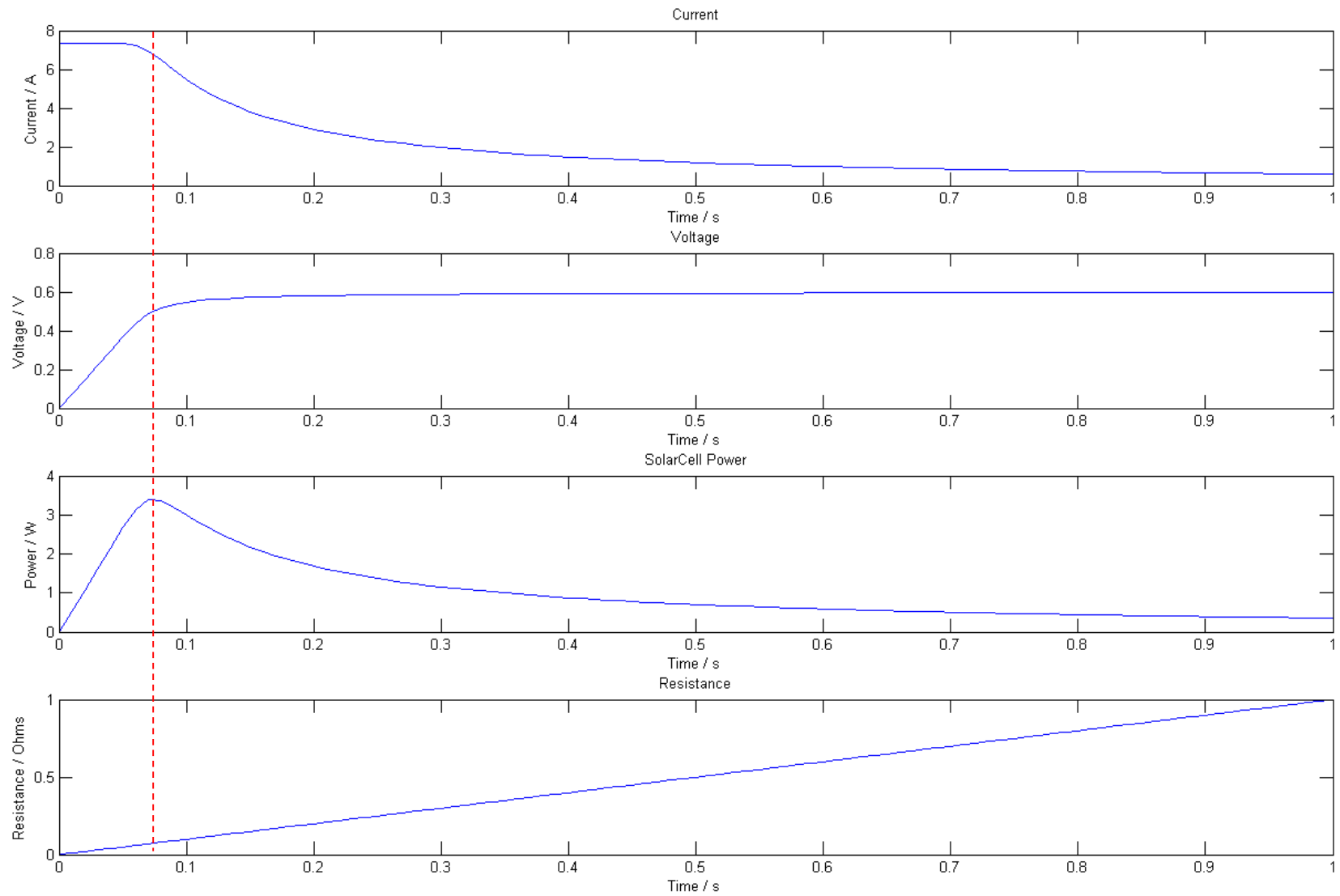


Figure 44: I , U , P and optimum resistance of a solar cell at STC

The following variables are obtained in the MATLAB workspace:

| Workspace | | | | |
|-----------|----------------|--------|--------|--|
| Name ▲ | Value | Min | Max | |
| Current | 10001x1 double | 0.0600 | 7.3400 | |
| Power | 10001x1 double | 0 | 3.3962 | |
| Time | 10001x1 double | 0 | 100 | |
| Voltage | 10001x1 double | 0 | 0.5997 | |

The following calculations are necessary for finding the optimum resistance for the simulated system:

```
maxPower = max(Power);
% inserts the maximum power value in the MaxPower variable

index = find(Power==maxPower);
% inserts in the index vector the positions of maximum power

U_opt = Voltage(index); % optimum voltage for the maximum power
I_opt = Current(index); % optimum current for the maximum power
R_opt = U_opt/I_opt; % optimum resistance for the maximum power
```

At the end, these calculations give the following results:

| Workspace | |
|-----------|--------|
| Name ▲ | Value |
| I_opt | 6.8208 |
| maxPower | 3.3962 |
| U_opt | 0.4979 |

| Workspace | |
|----------------|--------|
| Name ▲ | Value |
| maxPower | 3.3962 |
| Resistance_opt | 0.0730 |

It is verified that the results of the graphs correspond to the analytical results. For the proposed system, the optimum resistance for achieving the maximum output power of 3.3962 W would be 0.0730 Ω. Next, the purpose is to extend this process for any given irradiance in order to build the truth table for our MPPT model, which must contain the optimum resistance values that correspond to each value of irradiance.

The method used is a simulation-loop considering an irradiance range from 0 to 1200 W/m² in hundreds. This can be made by the simple program with MATLAB that follows:


```

n_runs      = 13;
mppPoint    = zeros(2,n_runs);
% create a 2xn_runs matrix to store the evaluated radiation values and
% its correspondent R optimal

for i=1:n_runs
% repeats the simulation n_runs times

    irradiance = ((i-1)*100)+0.0001;
    % irradiance values 0- 1200 kW/m² in hundreds

    simOut      = sim('solarcell_v1.slx');
    % simulation of the model from Fig. 5-20

    maxPower    = max(Power);
    % inserts the maximum power in the MaxPower variable

    index       = find(Power==maxPower);
    % inserts in the index vector the positions of maximum power

    mppPoint(1,i) = irradiance;
    % inserts the evaluated irradiance values in the first row of the
    mppPoint matrix

    mppPoint(2,i) = Resistance(index(1));
    % inserts the optimal resistance values in the second row of the
    mppPoint matrix
end

```

By this program and with a running time of 1000 seconds for each simulation (to make sure that the resistance reaches its optimum value), the Table 6 is obtained.

Table 6: Irradiance values and their corresponding optimum resistances for MPP

| Irradiance (W/m ²) | 0,0001 | 100 | 200 | 300 | 400 | 500 | 600 | 700 | 800 | 900 | 1000 | 1100 | 1200 |
|-----------------------------------|--------|------|------|------|------|------|------|-----|------|------|------|------|------|
| Optimum resistance (Ω) | 295,18 | 0,62 | 0,33 | 0,22 | 0,17 | 0,14 | 0,12 | 0,1 | 0,09 | 0,08 | 0,07 | 0,07 | 0,06 |

It is necessary to comment that the concrete case of $G \approx 0$ would theoretically correspond to a R_{opt} that tends to infinity, but if the value of irradiance is set to zero the simulation leads to an error because of division by zero. This is the reason of using an initial value of $G = 0.0001 \text{ W/m}^2$. For more precision, the irradiance values could be evaluated by any other lower range.

5.2.2.3 Implementation

The truth Table 6 can be implemented by the Simulink block called “1-D Lookup Table”, which maps inputs to an output value by looking up or interpolating a table of values.

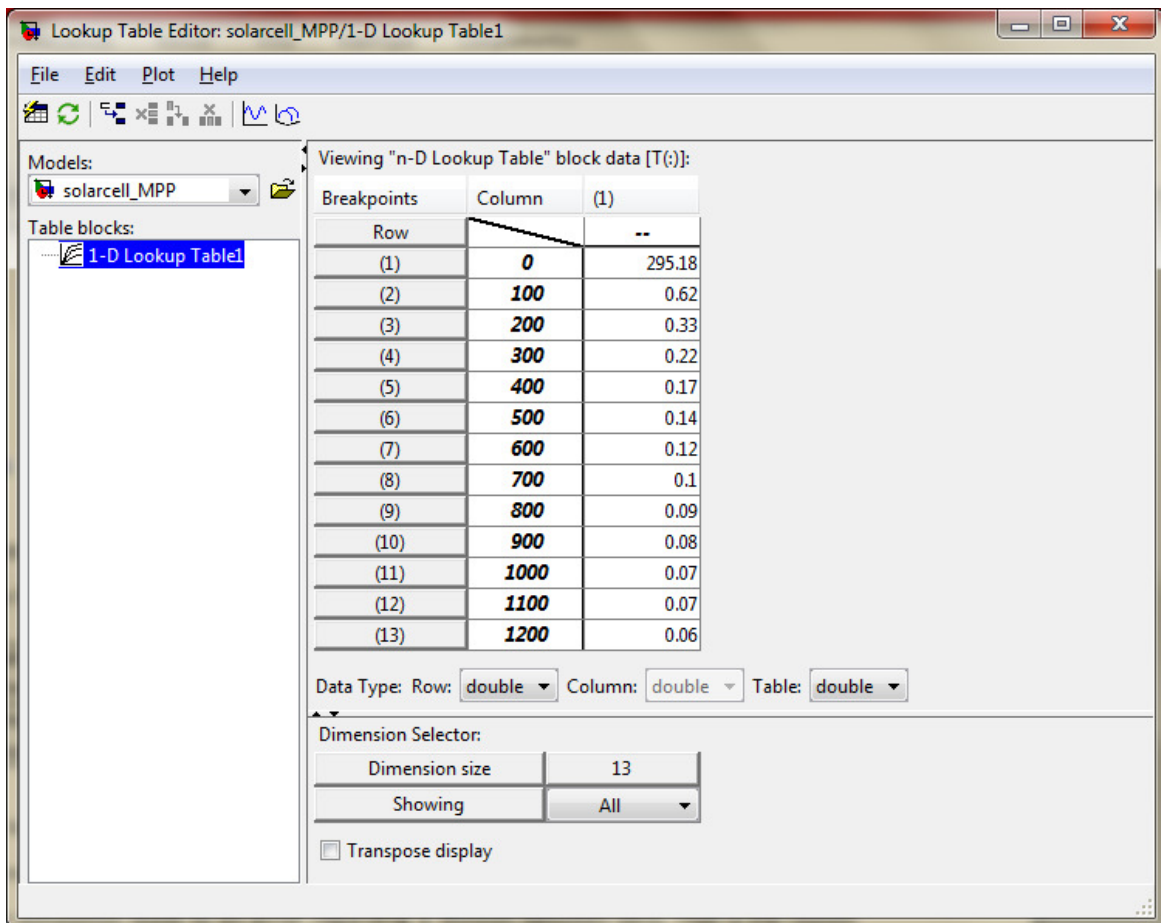
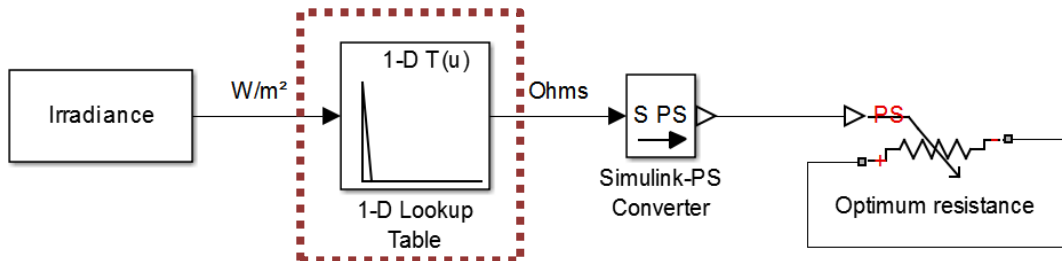


Figure 45: Appearance and main editor tab of the “1-D Lookup Table” Simulink block

This look-up table will represent the MPPT and it applies at every instant the optimal resistance that corresponds to any input irradiance. It must be implemented in the PV system as shown in Figure 46.

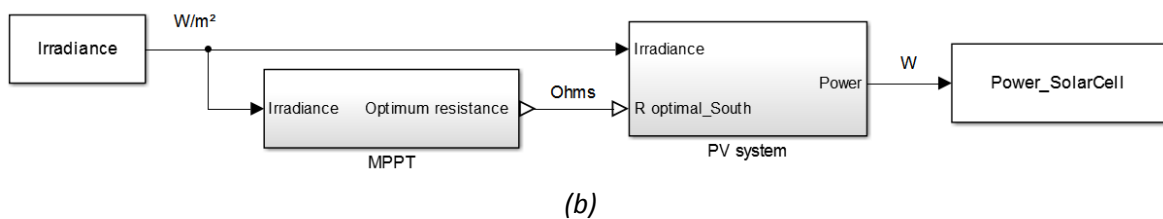
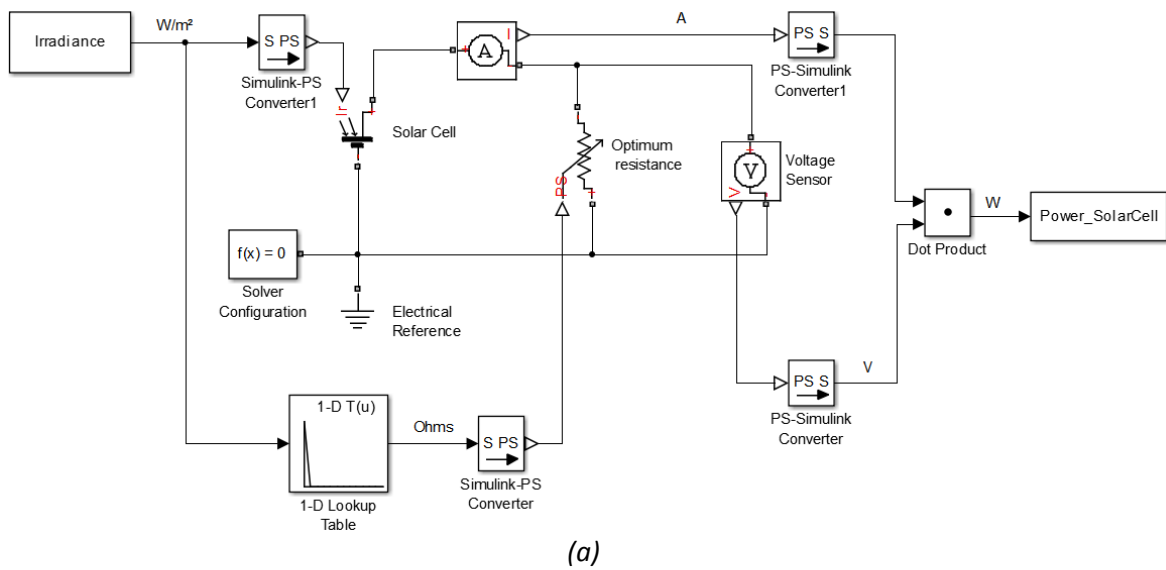


Figure 46: Implementation of the designed MPPT in the PV system;

a) Complete model; b) Model simplified

After simulating the model from Figure 46 by using the south irradiance data from the Hochschule Osnabrück along a whole day as input, this irradiance and the results of the total power generated and the optimum resistance for one solar cell are represented in the Figure 47.

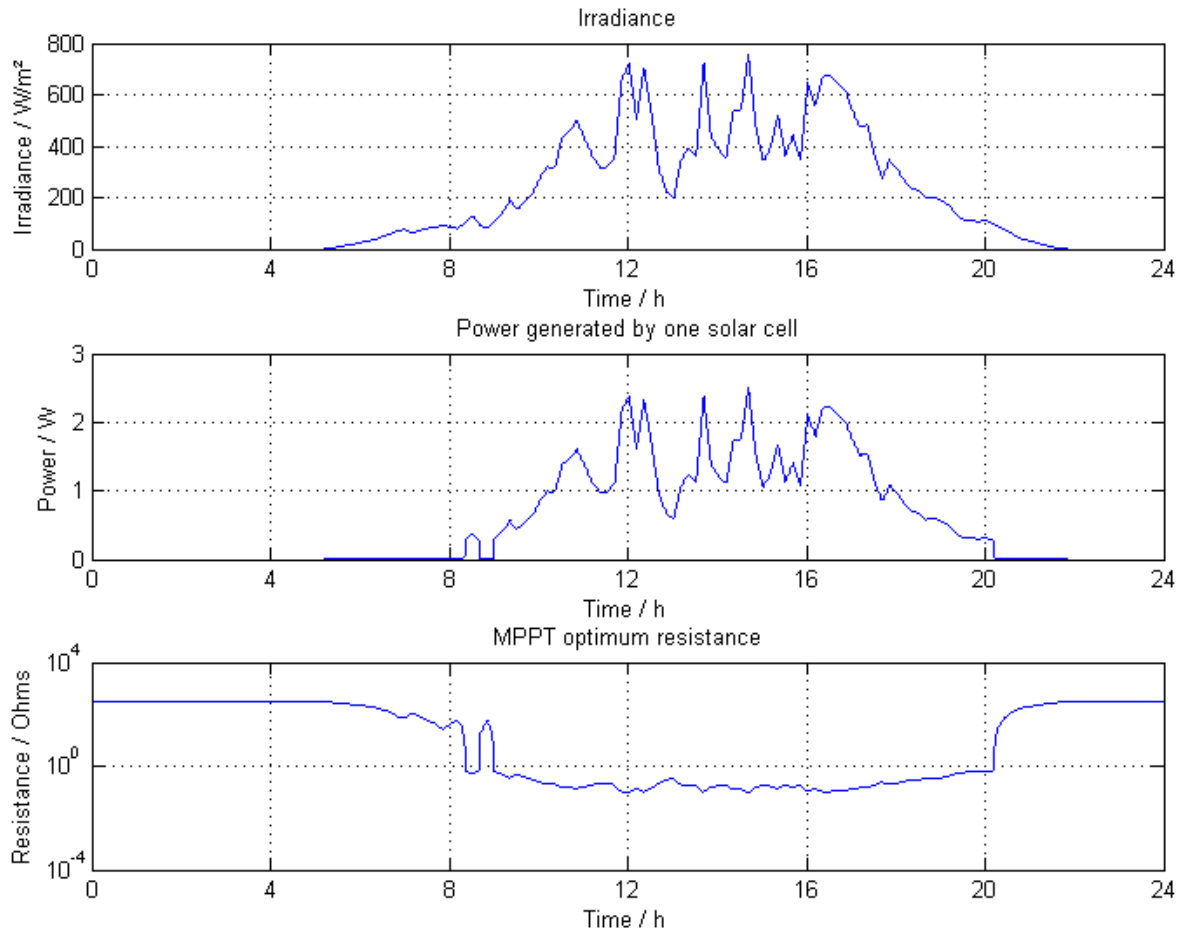


Figure 47: Irradiance, power generated and MPPT optimum resistance for one solar cell with south orientation over a day

The optimum resistance is represented in a logarithmic scale in order to visualize clearer its variations. Before coming to a conclusion about the operation and efficiency of the MPPT designed, in the next section east-west and south orientated PV systems with MPPT are compared.

5.2.2.4 Comparison of East-West and South PV Systems

The source for the east-west and south irradiance data is the PV-GIS solar radiation database [14]. The location selected is Osnabrück (Germany) and the values correspond to the average irradiance over one day in July 2013, as in the 4.1.2 section.

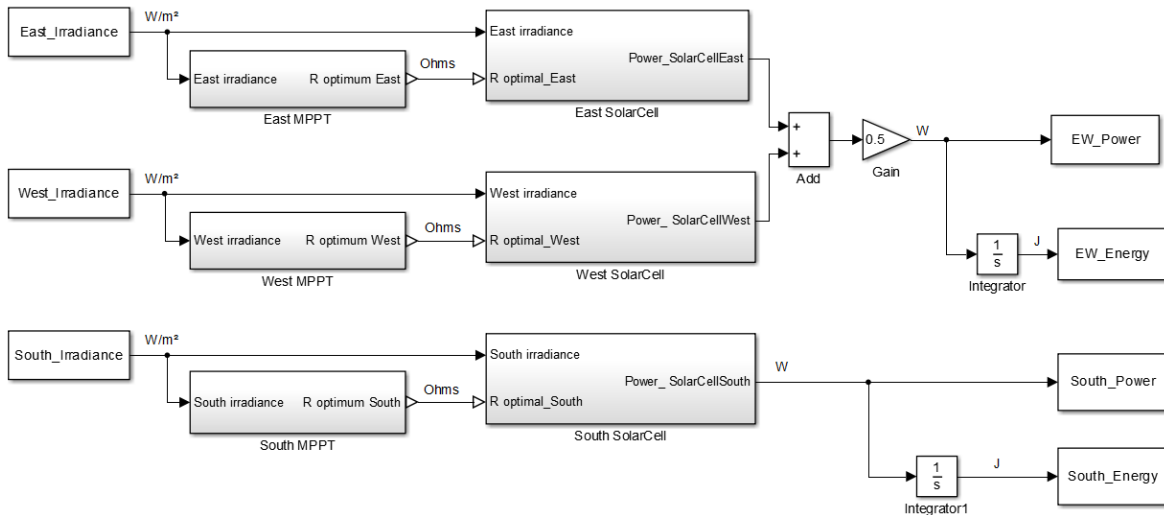


Figure 48: East, west and south PV systems with MPPT simplified models

Looking at the Figure 47 and Figure 49, it can be said that the MPPT designed has two main drawbacks: firstly, it is obvious that it is not pragmatic to build a truth table each time that the PV technology and/ or the number of solar cells are changed within the system. Secondly, if more accurate results are needed, the simulation loop must be done by smaller steps, which leads to a slower simulation. This will allow to build a more extensive truth table and the efficiency of the MPPT and thus of the PV system will be increased. This second deficiency can be observed at the Figure 47 and Figure 49: it is noticeable that when the irradiance is very low, the power generated is nearly zero, and as the irradiance gets higher in some point the resistance decreases abruptly. This effect is unrealistic and it is caused by the inaccuracy of the optimum resistance calculated for these low irradiance values.

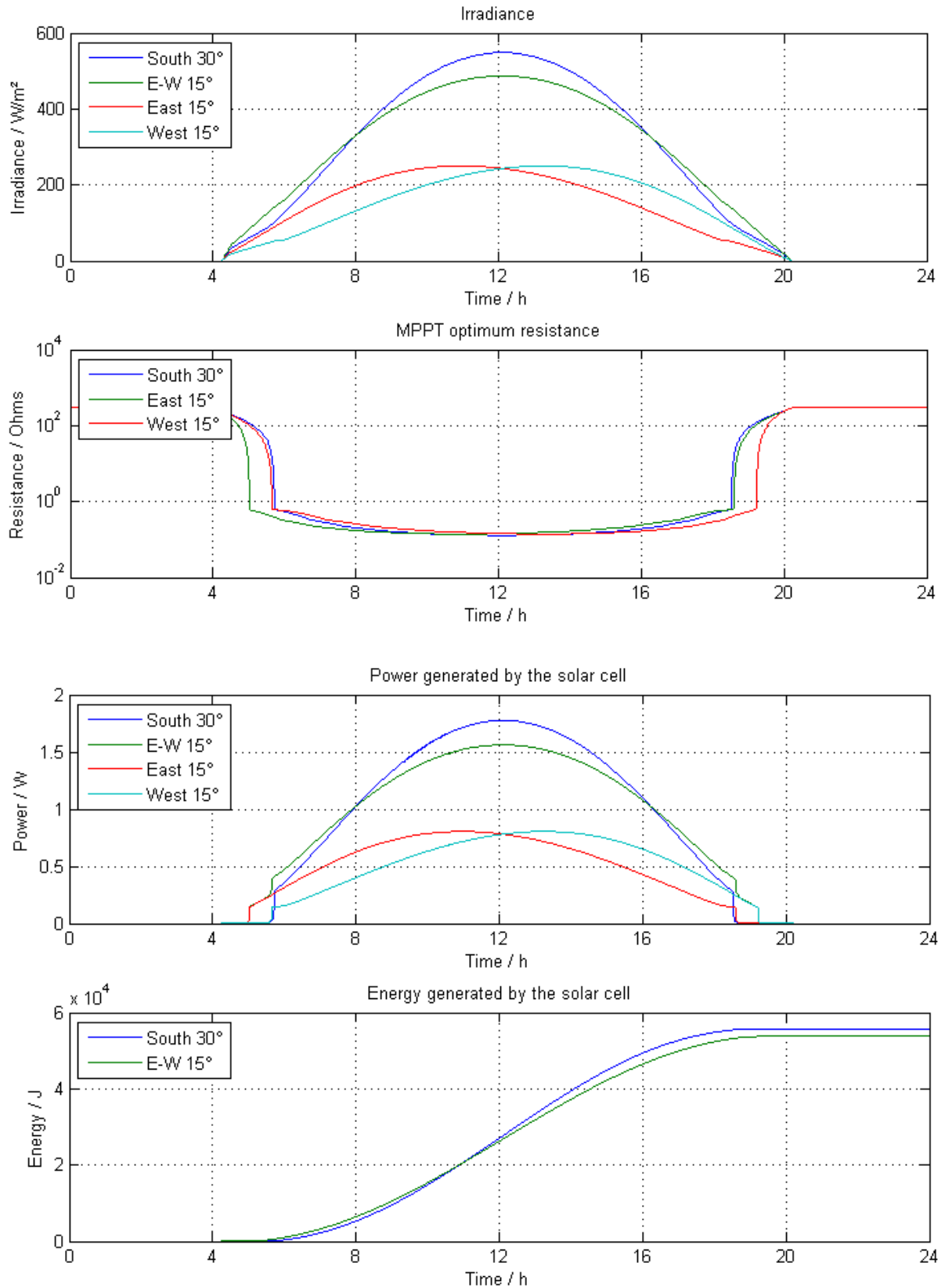


Figure 49: Irradiance, optimum MPP resistance, power and energy generated by east, west and south orientated PV systems with MPPT

5.2.2.5 Efficiency of the PV System

The equation for calculating the efficiency of a PV system is the following:

$$\eta = \eta_{\text{solar_cell}} \cdot \eta_{\text{inverter}}$$

With: $\eta_{\text{solar_cell}} = \frac{P_{\text{mpp}}}{G \cdot A_c}$ at STC $\eta_{\text{inverter}} = \frac{P_{\text{out}}}{P_{\text{in}}}$

Where:

- P_{mpp} power output of the solar cell at its MPP (W)
- G input irradiation (W/m²)
- A_c surface area of the solar cell (m²)
- P_{out} Inverter output power (W)
- P_{in} Inverter input power (W)

- The theoretical efficiency of the PV system:

$$\eta_{\text{theoretical}} = \eta_{\text{solar_cell}} \cdot \eta_{\text{inverter}} \approx 0.17 \cdot 0.96 = 0.1632 \approx 16\% \quad [13]$$

- In the simulation the efficiency of the PV system can be calculated with the results obtained from Figure 49:

$$\begin{aligned} \max(\text{Power_SolarCellSouth_30}^\circ) &= 1.7772 \text{ W} \\ \max(\text{Irradiance_South_30}^\circ) &= 549 \text{ W/m}^2 \end{aligned}$$

Therefore: $\eta_{\text{solar_cell}} = \frac{P_{\text{mpp}}}{G \cdot A_c} = \frac{1.7772 \text{ W}}{549 \frac{\text{W}}{\text{m}^2} \cdot 0.02 \text{ m}^2} = 0.1618 \approx 16\%$

There is no inverter in the system and the efficiency of the designed MPPT (component that is implemented within the inverter in the reality) cannot be calculated because its output is a resistance. Then, if an efficiency of 100% is chosen for the inverter in the simulation, the efficiency of the PV system in the simulation is the following:

$$\eta_{\text{simulation}} = \eta_{\text{solar_cell}} \cdot \eta_{\text{inverter}} \approx 0.16 \cdot 1 = 0.16 = 16\%$$

In conclusion, both the theoretical efficiency and that in the simulation are practically equal.

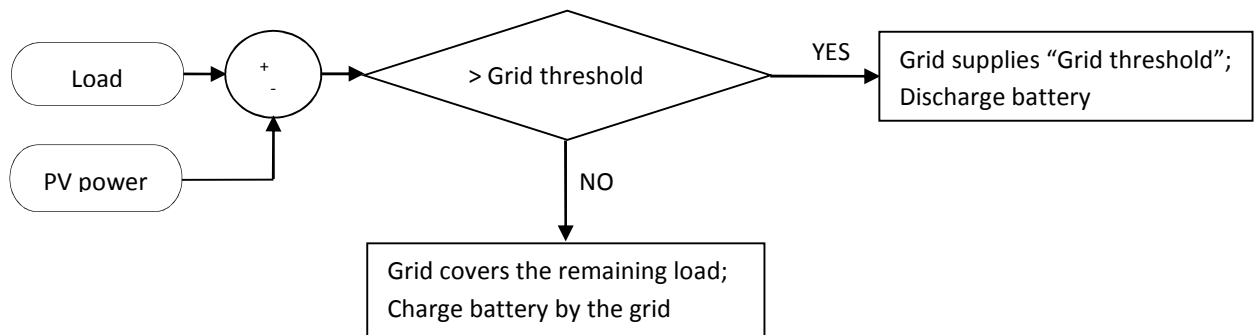
5.2.3 Controller

5.2.3.1 Objective

The controller is the brain of the whole system and it has to obey the following operation conditions:

- The PV power generated must be always used when possible.
- The battery is discharged when the grid demand after having supplied all the PV power is still higher than the grid threshold.
- The rest of the consumption not covered by the PV system nor by the battery must be covered by the grid.
- The battery is charged by the grid when the remaining load after having supplied all the PV power is lower than the grid threshold.

These conditions can be represented by the following block diagram:



Therefore, the controller must decide firstly which component(s) will cover the load demand (the battery, the PV system or the grid) and the amount of power that each component must supply. Secondly, it has to distinguish whether the battery needs to be charged or not by the grid, and if yes in which quantity.

As explained previously in the section 5.2.1, the “base” of the demand will be covered by the grid until this demand exceeds the arbitrary *threshold power* defined. Above this limit there are the so called “peaks” that must be covered by the PV system or, if necessary, by the PV system and the battery if the SOC of the battery is within its permissible limits. If even with the PV system and the battery support is not possible to cover the whole

demand, then the grid must provide the necessary *Grid exceeding threshold* that exceeds the *grid threshold* for covering it completely.

In addition, while obeying these tasks at every moment, the model of the battery has to comply with the next conditions:

- The battery must not be overcharged
- The battery must not be deeply discharged
- The battery nominal charging power must not be exceeded
- The battery nominal discharging power must not be exceeded

The aim of the two first conditions is to avoid the damage of the battery in case of being overcharged or deeply discharged. In order to avoid this danger it is important to maintain its SOC within fixed limits. These limits may be different depending on the specific battery.

Secondly, the reason of controlling the maximum charging and discharging power lies on the effective capacity of the battery. These variables will be set by the rate of charge and discharge of the battery, which have a high influence on the effective capacity of a battery: it is reduced at high rates or conversely increased with low rates. This is called the capacity offset and the effect is common to most cells.

These four conditions given for the battery are usually made by the solar battery controller in the reality.

To fulfil all these specifications, the control is divided in two controllers or functions which will be interconnected very closely and will operate in a coordinated way within the whole system at every moment: these are the main controller and the secondary controller.

5.2.3.2 Design

In the present section, for defining each controller model, the following steps are taken: firstly, it is necessary to analyse the necessary functions or tasks that the controllers must fulfil. Secondly, the inputs and outputs must be defined carefully. Then, after analysing the relationships between the different variables and their functions, they all must be incorporated in an orderly way within a program. Finally this program will be implemented in Simulink by the MATLAB function component, which will shape the model of the particular controller.

5.2.3.2.1 Main Controller

The first controller is called the *main controller* and its functions are described in this paragraph. Firstly it must decide which component/s must cover the load demand: the grid, the PV system, the battery, or a combination of them. Secondly, it must calculate the different amounts of power that each power source must supply to the load. And thirdly, it has to distinguish whether the battery needs to be charged or not, and if yes, calculate the kilowatts that the grid must inject for charging it without disobeying the specifications of the battery.

Table 7: Inputs and outputs for the model of the main controller

| Inputs | Outputs |
|--|---|
| <ul style="list-style-type: none"> • Load of the company (demand) • Power generated by the PV system • State of charge of the battery (SOC) • Grid threshold power • SOC minimum for the battery • SOC maximum for the battery | <ul style="list-style-type: none"> • PV power subtracted from the load • Power supplied by the grid for charging the battery • Power that is still necessary to be supplied after having injected all the PV power for covering the demand |

The Table 7 can be represented by a MATLAB model as it follows:

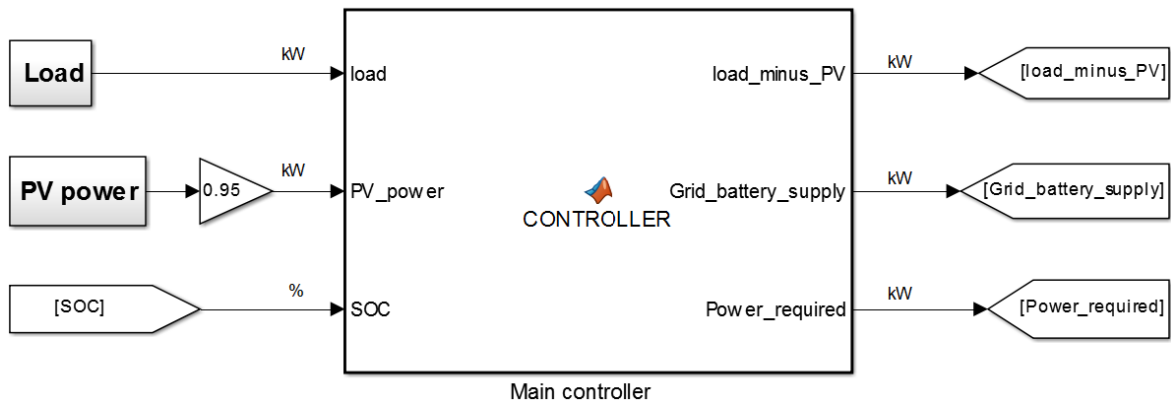


Figure 50: Model of the main controller for the PV system

In the Figure 50, the variables that are introduced directly from the workspace in the Simulink model are showed by quadrangular-shape boxes. The rest of the variables are generated during the simulation, and they are represented by arrow-shaped boxes. The triangle linked to the PV power represents the efficiency of the inverter (the efficiency of the solar modules was already included in the solar cell model). In this case the efficiency of the inverter is set to 95 % [13].

A definition of the labels given for the different variables chosen for the model of the present controller is presented below:

- Inputs

- *Load*, kW: Load of the company (demand that must be covered).
- *PV power*, kW: total power generated by the whole PV system.
- *SOC*, %: state of charge of the battery.

- Outputs

- *Load minus PV*, kW: power that results from subtracting the total *PV power* generated to the *load*.

- *Grid battery supply, kW*: total power supplied by the grid for charging the battery. This value is calculated as the *Load minus PV* subtracted to the *grid threshold*. It represents the power from the grid that can be used for charging the battery, without exceeding the *grid threshold*, after having already covered the whole demand.
- *Power required, kW*: power that cannot be covered only by the *grid threshold* or by the *grid threshold* together with the *PV power*. It is calculated by subtracting to the total load the sum of the *grid threshold* and the total *PV power*. Thus if its value is higher than zero, it must be covered by the battery if possible, and if not possible then by the *Grid exceeding threshold*. It can be represented graphically as in the Figure 51.

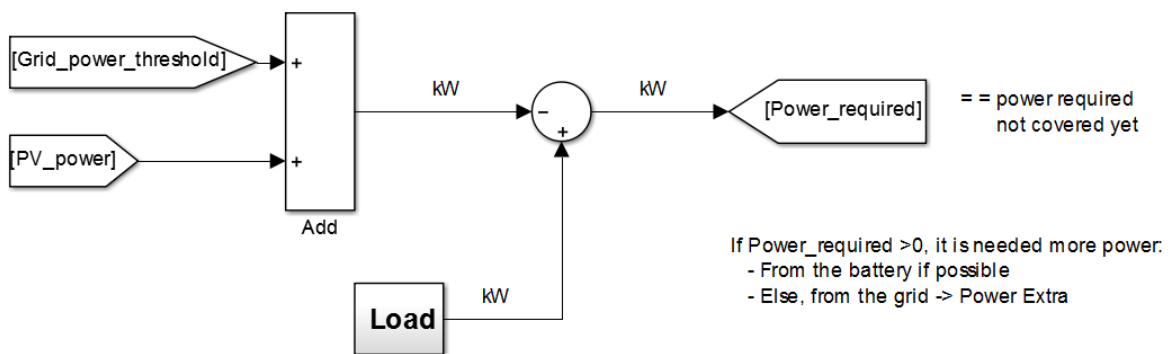


Figure 51: Model for obtaining the “Power required” variable

Inside the Simulink model defined in the Figure 50 by the MATLAB function component, a program that can be found in the Appendix 1: Main controller program has been built. This program is analogue to the following block diagram.



Primary inputs

- Load
- PV power
- Grid threshold
- SOC max
- Battery charge rate

Secondary inputs

- SOC

Auxiliary variables

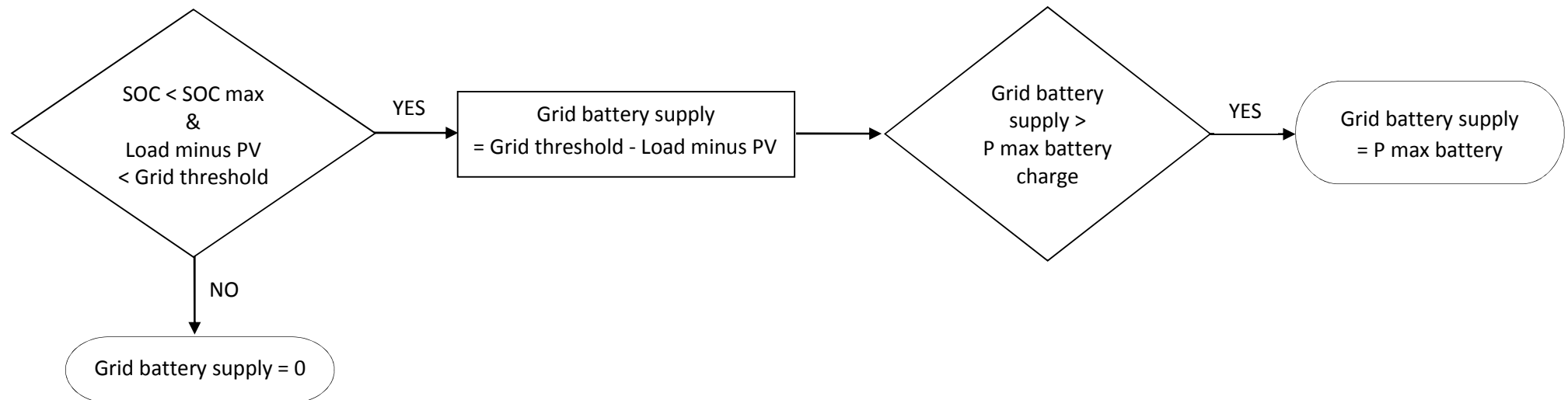
- Load minus PV

Outputs

- Grid battery supply
- Power required

$\text{Load_minus_PV} = \text{load} - \text{PV_power};$

$\text{Power_required} = \text{load_minus_PV} - \text{Grid_power_threshold};$



5.2.3.2.2 Secondary Controller

The *secondary controller* is mainly related to the battery operation. It must decide whether the battery must be discharged and if yes, in which quantity. It must also protect the battery from being from being deeply discharged. Finally, it also has to calculate the necessary *Grid exceeding threshold* in case of necessity.

Table 8: Inputs and outputs for the secondary controller model

| Inputs | Outputs |
|---|---|
| <ul style="list-style-type: none"> • Power required • State of charge of the battery (SOC) • Supply for the battery • SOC minimum for the battery • SOC maximum for the battery • Discharge rate for the battery • Charge rate for the battery | <ul style="list-style-type: none"> • Power that charges or discharges the battery • Power battery discharge • Grid exceeding threshold |

The Table 8 can be represented by a MATLAB model as it follows:

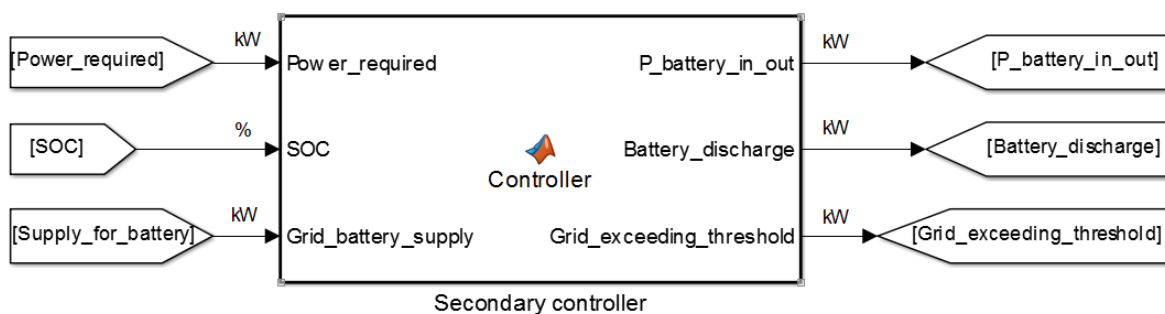


Figure 52: Model of the secondary controller for the PV system

Again, a definition of the labels given for the different variables chosen for the controller model of represented in the Figure 52 is presented below:

- Inputs

- *Power required*, kW: only when its value is positive, it corresponds to the power that cannot be covered only by the *grid threshold* or by the *grid threshold* together with the *PV power*.
- *SOC*, %: state of charge of the battery.
- *Supply for battery*, kW: total power supplied by the grid for charging the battery.

- Outputs

- *Power battery in / out*, kW: power that charges and discharges the battery (battery input and output power). This value is positive while charging and negative while discharging.
 - *Power battery discharge and protection*, kW: auxiliary variable for calculating *power battery in / out*. As its name suggests, this variable discharges the battery, but also protects it from being deeply discharged. Its action on the battery input and output power together with the already presented *supply for battery* variable is represented in the Figure 53. In addition, the discharge of the battery along the time (*battery discharge* variable) can be calculated by introducing the values of the *Power battery discharge* variable when the battery is not being charged, which means, the *supply of the battery* variable is zero. This whole operation is implemented within the secondary controller.

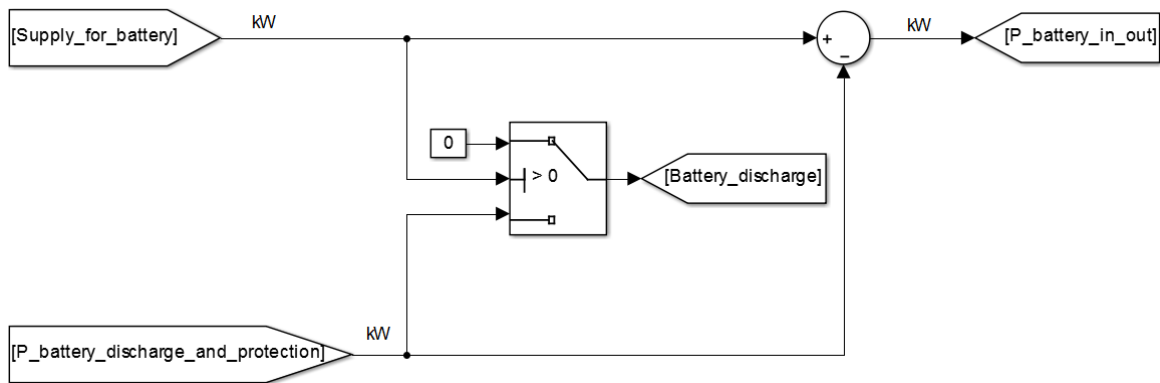
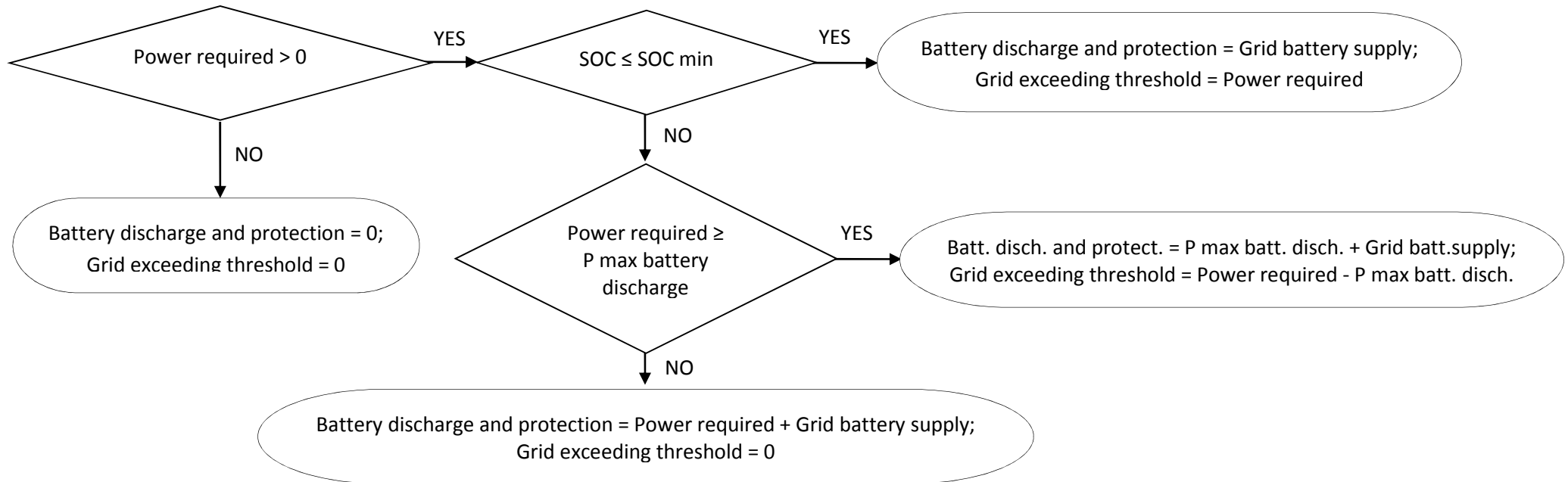


Figure 53: Model of the charge and discharge control of the battery

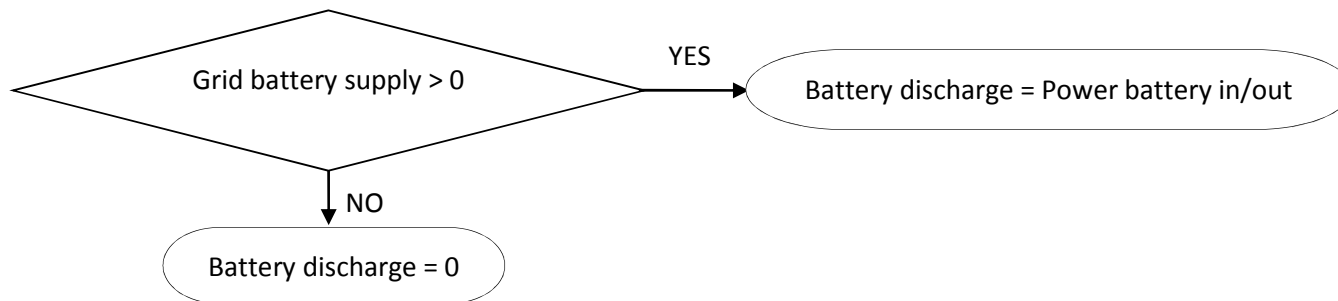
- *Battery discharge, kW*: total power supplied by the battery for covering the peaks of the demand.
- *Grid exceeding threshold, kW*: power provided by the grid besides the *grid threshold*. This fraction of the power demanded exceeds the *grid threshold* and is not being covered by the PV system nor by the battery.

Inside the model of the Figure 52, a program that can be found in the Appendix 1: Main controller program has been built. This program is analogue to the next block diagram, which has the following parameters:

| Primary inputs | Secondary inputs | Auxiliary variables | Outputs |
|--|--|--|---|
| <ul style="list-style-type: none"> • SOC min • SOC max • Battery discharge rate | <ul style="list-style-type: none"> • SOC • Power required • Grid battery supply | <ul style="list-style-type: none"> • Battery discharge and protection | <ul style="list-style-type: none"> • Power battery in/out • Battery discharge • Grid exceeding threshold |



Power battery in/out = Grid battery supply - Battery discharge and protection;



The rest of the inputs that are missing in the models of both controllers can be initialized in another script, as their values remain constant over the time. In addition, these constant specifications for each concrete system can be easily set by the user at the beginning of each simulation by a graphical user interface (GUI), which will be shown in the next section.

Both controllers' models will be directly implemented with the rest of the components in the next chapter in order to model the whole system.

5.2.4 Graphical User Interface

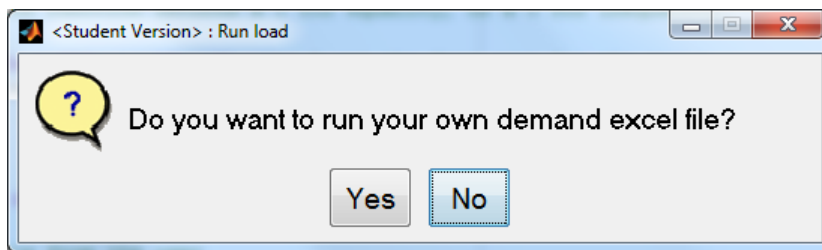
In order to help an inexperienced MATLAB user to run a simulation of the PV system model, a simple Graphical User Interface (GUI) is built. The user is allowed to introduce the desired parameters for the simulation by menus and dialog windows displayed by the GUI.

The following conditions and parameters are set by this GUI:

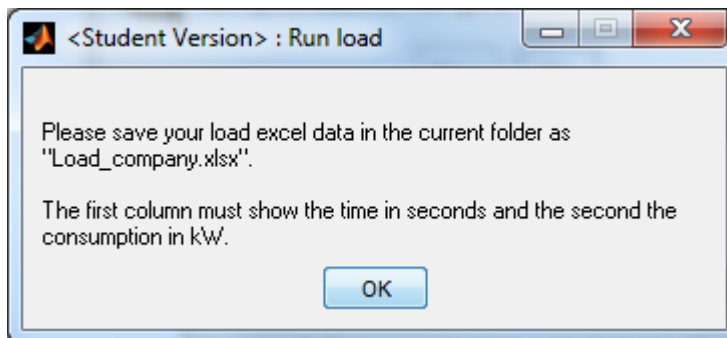
- Company load
- Grid power threshold
- Irradiance for the month selected
- PV system specifications
 - Orientation
 - Inclination
 - Rated power
- Battery specifications
 - Rated capacity
 - SOC minimum
 - SOC maximum
 - Charge rate
 - Discharge rate

Next some screenshots are presented in order to see the operation of the GUI:

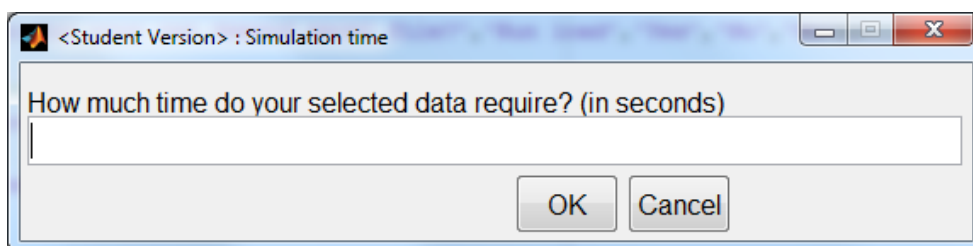
At the beginning, the user must choose or/ and introduce all the input data. Firstly, the user can load his own consumption data for running the simulation. If so, he must save an excel file in the file where the GUI program is found and this excel must content the time (in seconds) in the first column and the power consumption (in kW) in the second column.



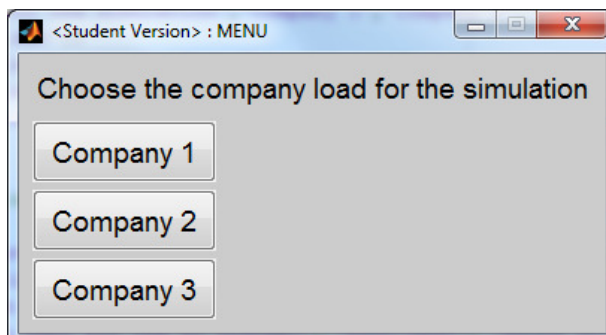
In case of 'Yes':



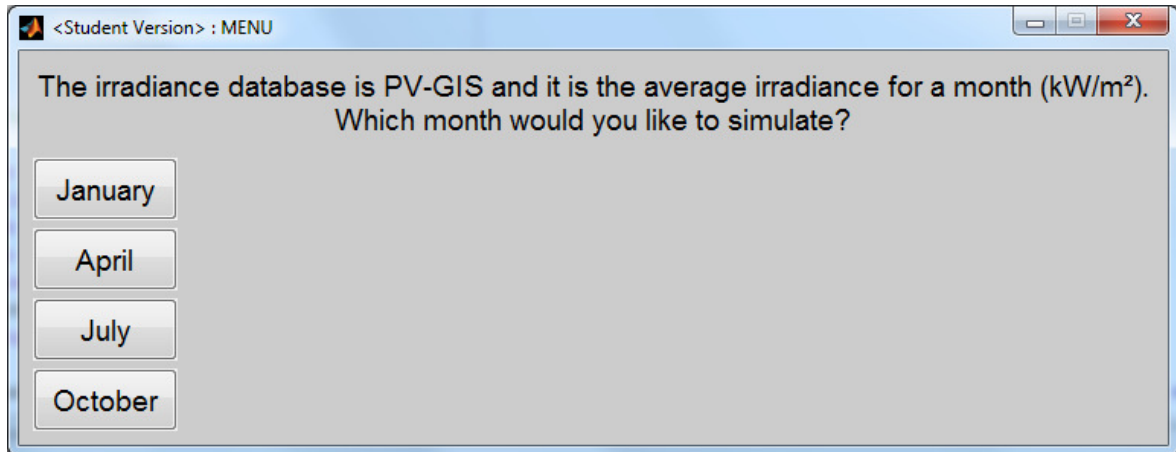
The time required for the data regards to the total simulation time.



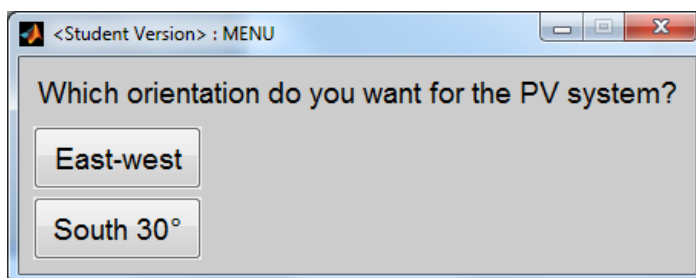
In case of 'No':



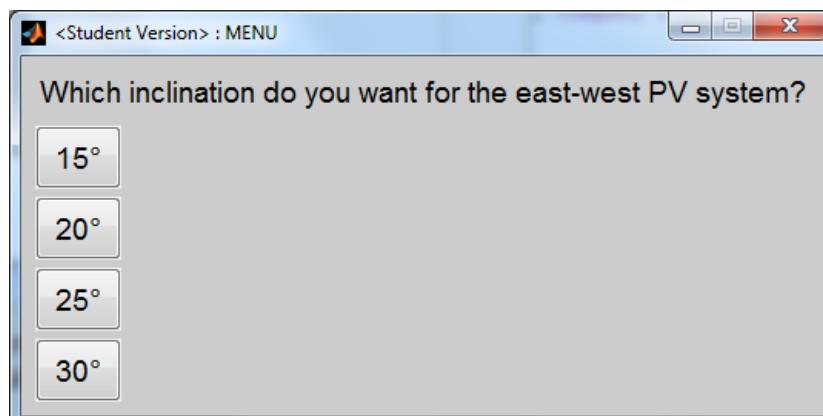
Next the season for the irradiance data must be selected. The months of January, April, July and October were selected because they do not belong to the most extreme climatological conditions and they are equidistant in time:



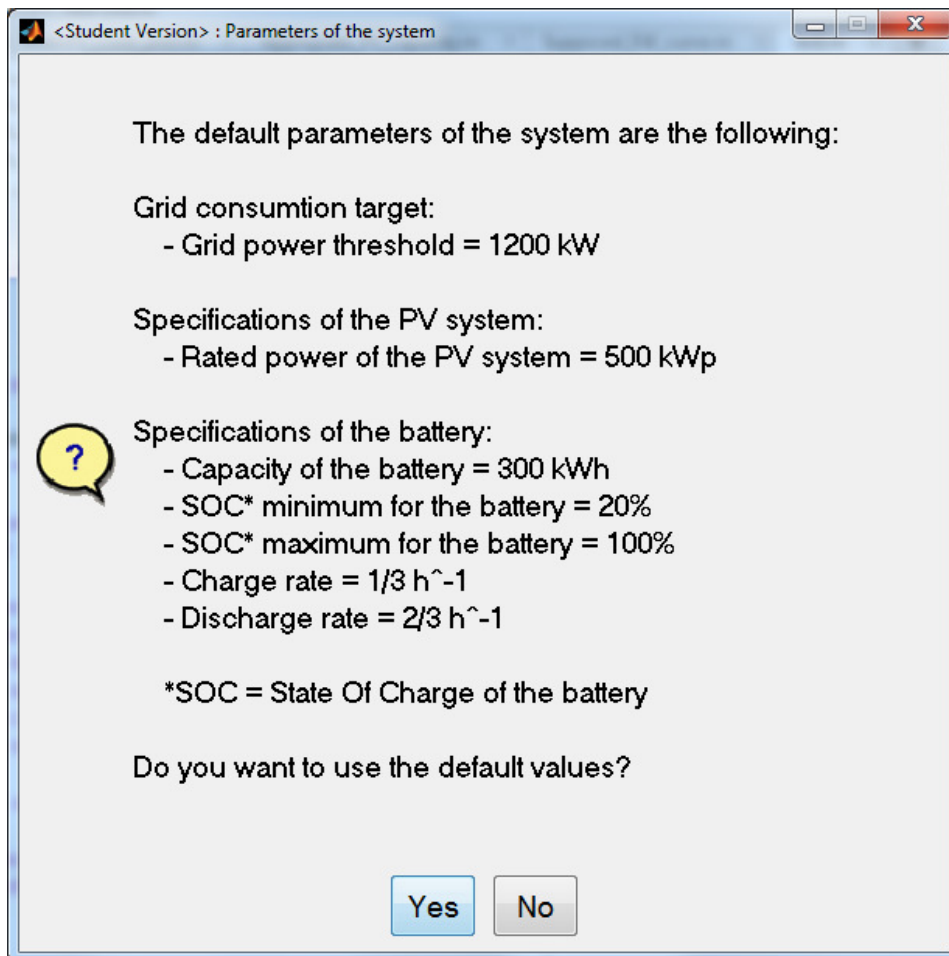
Then the orientation of the PV system can be chosen: E-W or south.



In case of 'South' only a 30° tilt angle can be chosen because this is the optimum inclination for the latitude of Osnabrück. In case of 'East-west' an inclination of 15°, 20°, 25° and 30° can be selected:

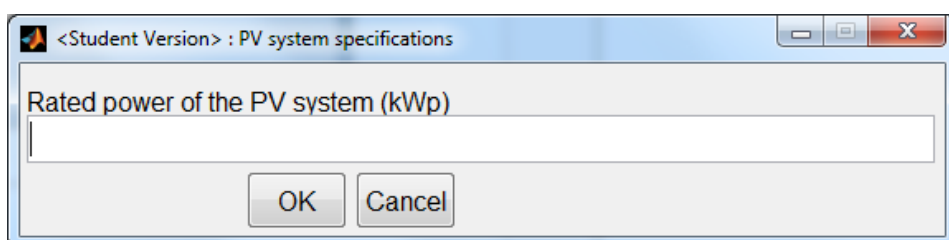
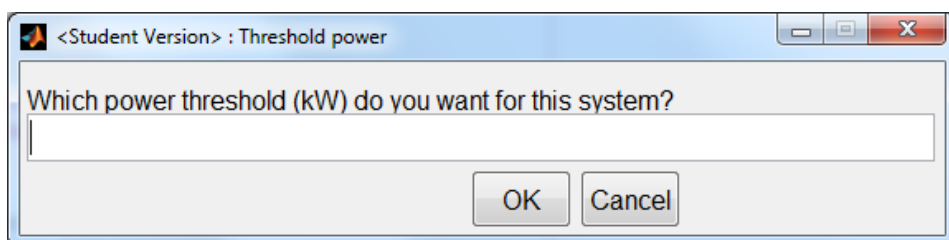


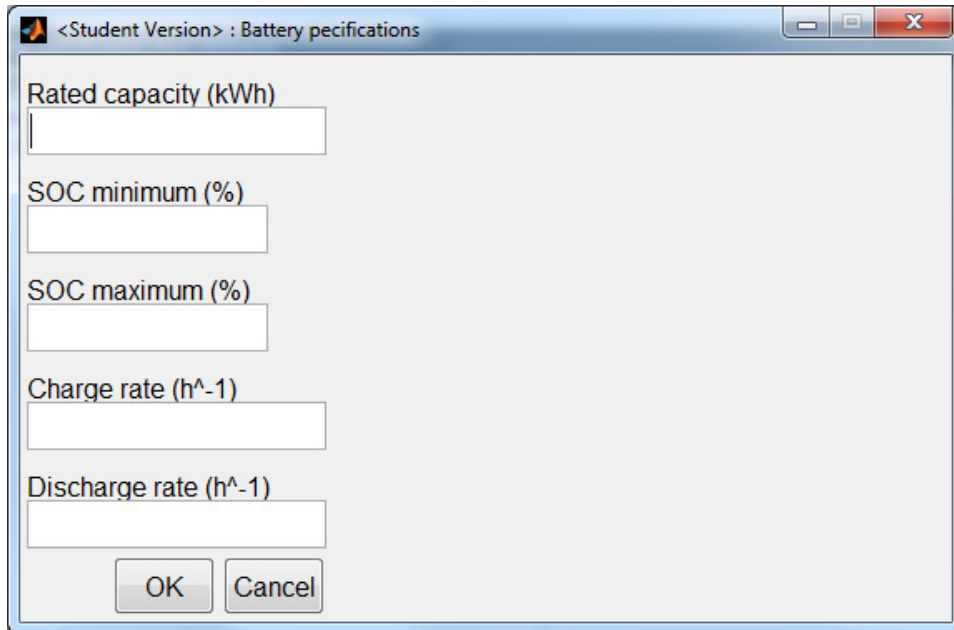
About the rest of the system parameters, the user can run a one-day simulation with the default values or introduce his desired parameters:



In case of 'Yes' these default parameters are run.

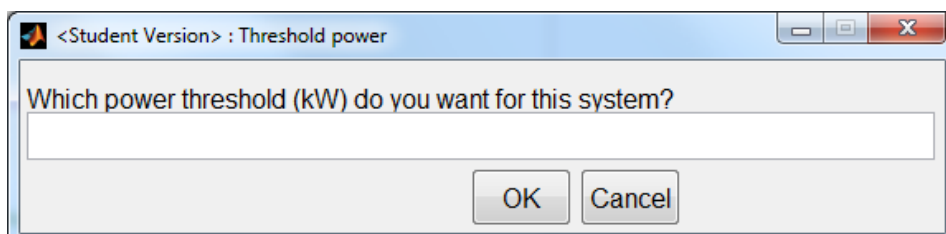
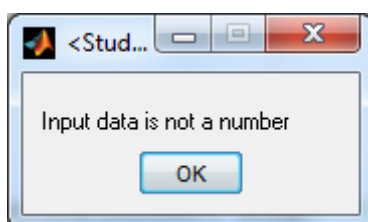
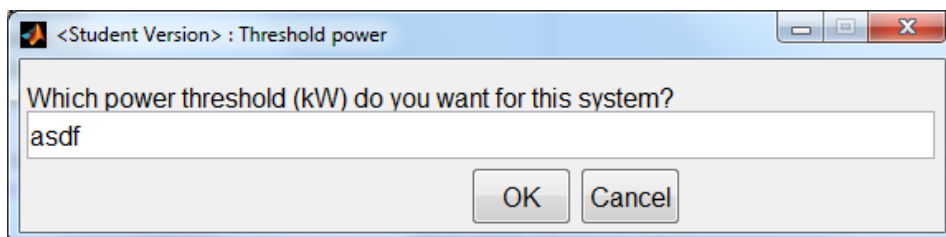
In case of 'No', the user must introduce his own specifications for the system manually:



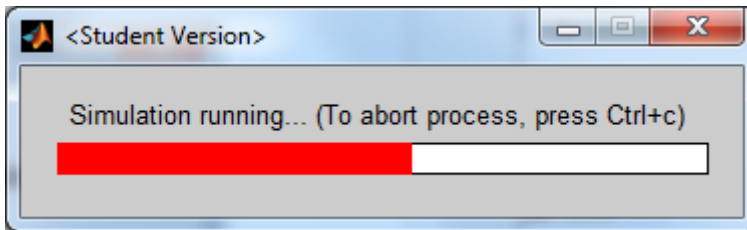


In addition, the program is prepared so that if an input is not a number in any of the dialog windows, an alert message is displayed and then the dialog window appears again.

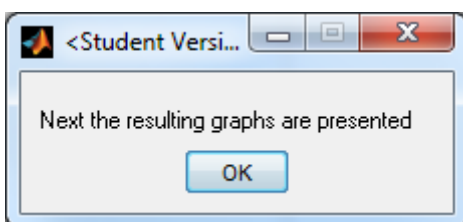
This is illustrated by the following example:



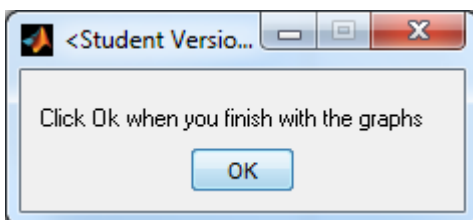
After introducing all parameters, the simulation starts automatically and a wait bar is displayed to inform about the estimated remaining time:



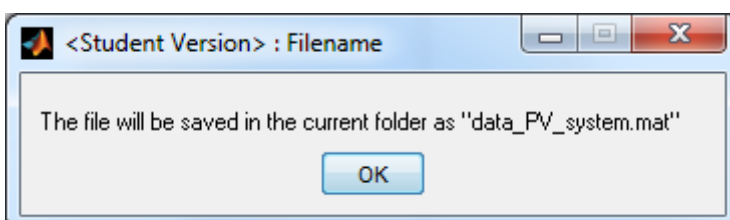
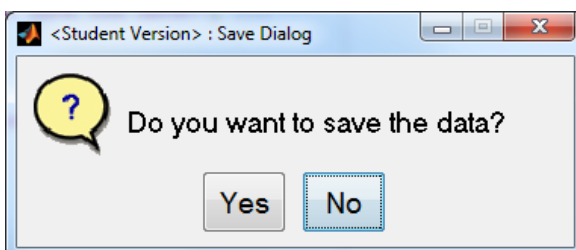
Next, three representative graphs are presented (see Figure 58 and Figure 59):



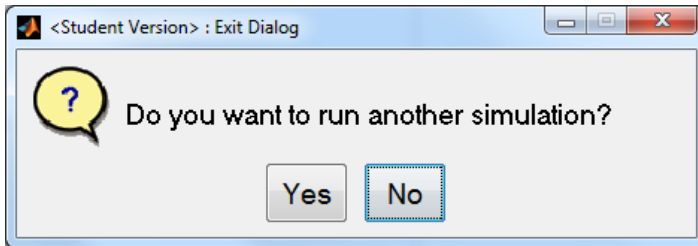
The program waits while the user is analysing the graphs until he clicks Ok in the following window:



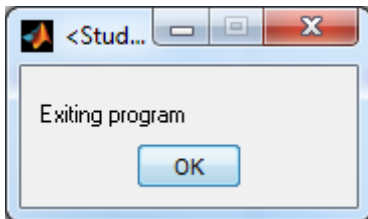
Afterwards it is possible to save the obtained data and if yes, the user is informed about the future filename and location of these data.



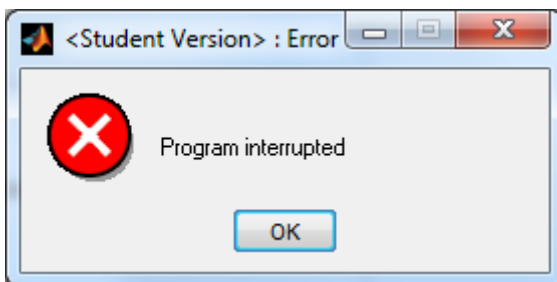
To finish, the user can choose whether he wants to run another simulation or not.



In case of 'Yes', the program starts again and in case of 'No' the program is closed.



At any time, if the user closes a window, the following message is displayed:



6 Simulation of the Complete PV System

6.1 Model of the Complete System

6.1.1 Block Diagram

In order to build the model of the whole system, it may be useful to draw firstly its block diagram in order to notice the connections between the different main components. This block diagram is represented in the Figure 54.

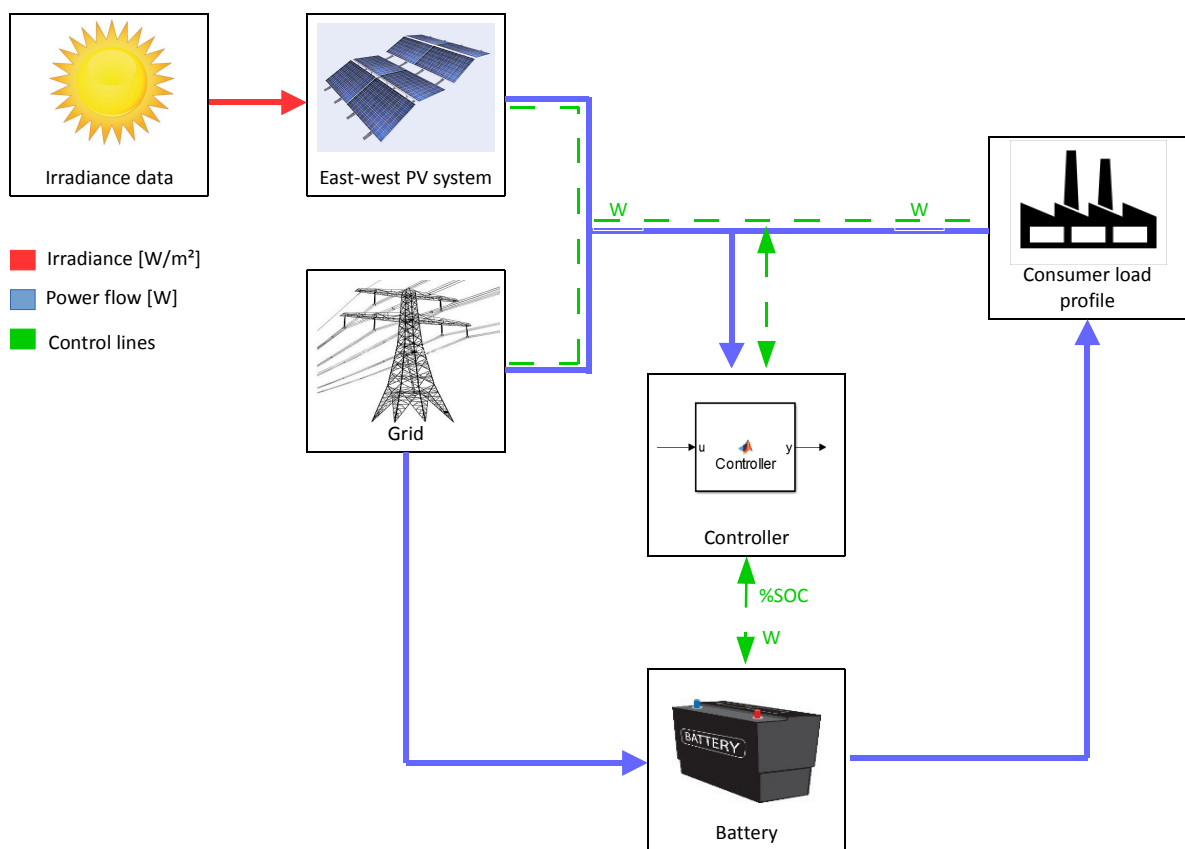


Figure 54: Block diagram of the simulation

The links between the components have been drawn distinguishing between power flow lines (in red and blue) and control lines (in green). Finally, both the *main controller* and the *secondary controller* are represented as a unique central controller.

Table 9: Inputs and outputs for the simulation of the complete system

| Inputs | Outputs |
|--|--|
| <ul style="list-style-type: none"> • Irradiance data kW/m² • Load profile kW • Grid threshold kW • Battery specifications <ul style="list-style-type: none"> ○ Capacity Ah ○ SOC min % ○ SOC max % ○ Charge rate h⁻¹ ○ Discharge rate h⁻¹ | <ul style="list-style-type: none"> • Total power supplied by the grid for <ul style="list-style-type: none"> - Covering the base of the demand kW - Charging the battery kW - Covering the peaks of the demand kW • PV power supplied for the load base kW • PV power supplied for the load peaks kW • Power supplied by the battery kW • Charge-discharge profile of the battery % |

About the Table 9, it must be noticed that all parameters are dynamic over the time except the *grid threshold* and the battery specifications, which are constant during the whole simulation for a given system.

All variables presented in the Table 9 have been already introduced and defined in the section 5.2.3.

6.1.2 Simulink Model

The implementation of the controllers in the whole system is made as shown in the Figure 55. Notice that in this model all the components are included unless the PV system with its MPPT, which can be simulated separately (for reasons of simulation speed) by the model exposed in the Figure 48. From this previous simulation, the resulting power generated can be saved for using it as an input for the present model. This means that for this second simulation the main components are the consumer, the grid, the battery and the controllers.



Figure 55: Simulink model of the whole system

In order to describe the model from the Figure 55, the focus is firstly put on the inputs: the power data generated by the solar cells (*PV power*) are directly taken from the saved results of the model simulation from Figure 48; results obtained with east-west and south irradiance will be compared further on. The *load* from the company is introduced directly, and the *grid threshold* target defined arbitrarily for being taken from the electric company and the battery specifications (*capacity*, *SOC_{min}*, *SOC_{max}*, *P_{nom charge}* and *P_{nom discharge}*) are defined separately by the GUI shown in the section 5.2.4.

Secondly, the different components that shape the model are organized and divided in three main parts depending on their functions in order to make the understanding of the whole system easier. These parts are the so called: main controller subsystem, secondary controller and battery (dis)charge subsystem and grid subsystem.

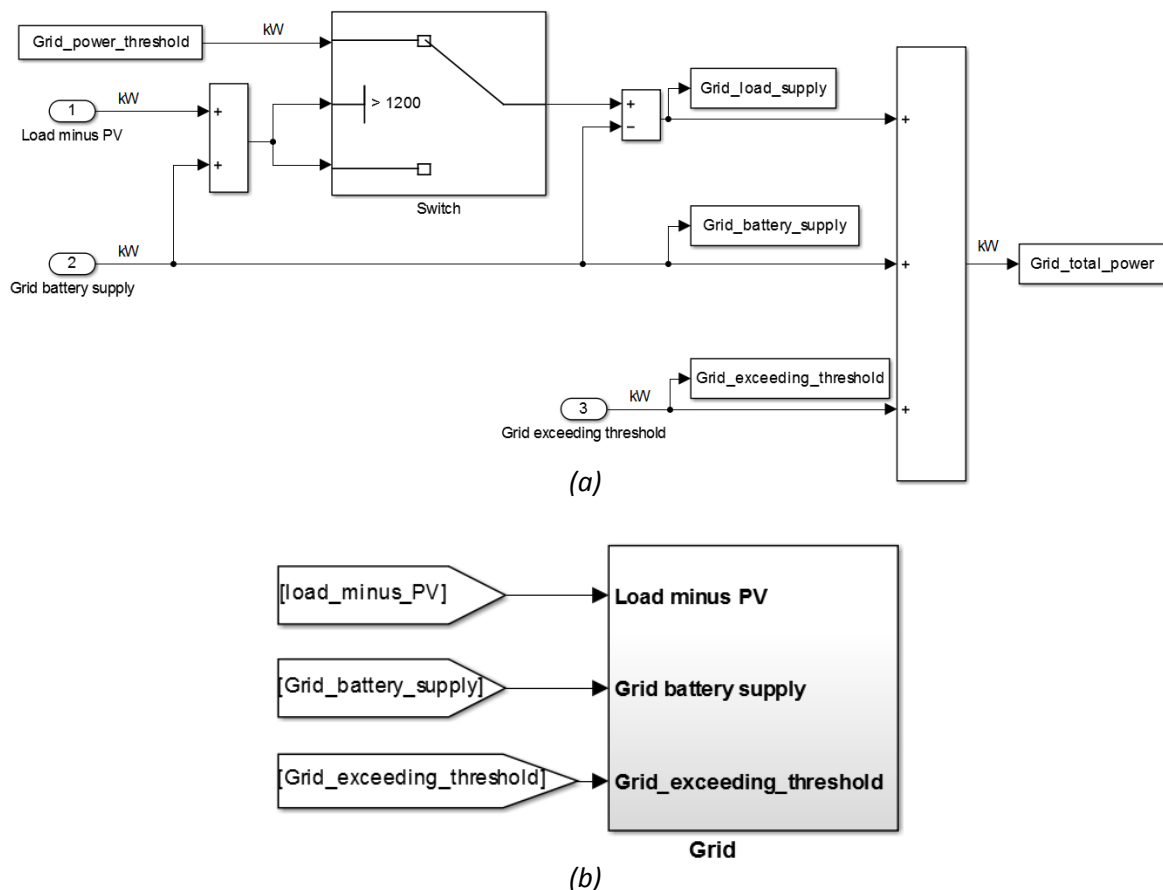


Figure 56: Simulink model of the implementation of the grid subsystem

a) Complete model; b) Model simplified

The main and secondary controllers have already been explained in the sections 5.2.3.2.1 and 5.2.3.2.2 respectively. About the battery (dis)charge, a battery efficiency of 87.5 % [13] is chosen (see triangle in Figure 55). The grid subsystem was clarified in the section 5.2.1 and its Simulink model is represented in the Figure 56.

6.1.3 Power Threshold Choice

Before running a simulation, a *Grid threshold* is necessary to be chosen. This value is arbitrary, but in order to make an appropriate choice, the following steps are recommended: firstly, choose a null solar irradiance in order to set the most demanding conditions for the system. The battery is the component that must assure the supply, independently of the solar irradiance, because this natural source is unpredictable. After setting the rest of the parameters of the system by the GUI, run a first simulation with a *grid threshold* equal to the result of subtracting the *battery nominal discharge power* from the *load maximum power*. Next, check whether the *grid power exceeding threshold* is higher than zero. If yes, choose a higher *grid threshold* and repeat the previous check until the *grid power exceeding threshold* is zero. Only then the *grid threshold* will be appropriate.

Example: a company load curve reaches its maximum peak with 1300 kW. The battery nominal discharge chosen is 200 kW (this corresponds to a discharge rate of 2C/3). Therefore, the *grid threshold* to be checked will be 1100 kW. As showed in the Figure 57, using no PV power, the *grid power exceeding threshold* is not zero and therefore the simulation must be repeated with a higher *grid threshold* (1150 kW in the example) until the *grid exceeding threshold* is zero. In the example this is achieved with a *grid threshold* of 1200 kW.

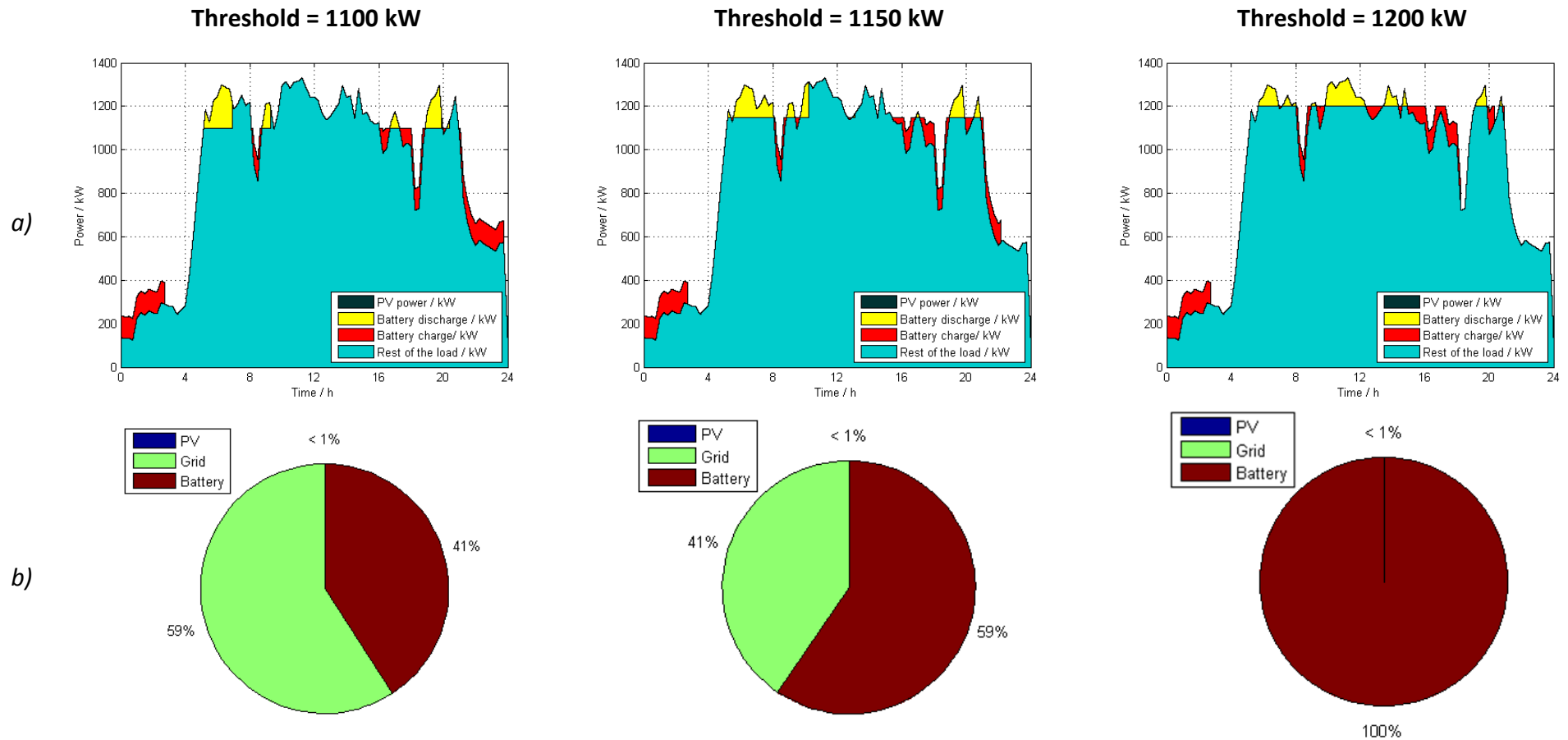


Figure 57: Steeps for the grid threshold choice

a) Load curve of a company and fractions covered by each component: PV system, battery and grid;

b) Percentage of the total power supplied above the Grid threshold by each power source;



6.2 Results and Analysis

In this section some examples of simulation are carried out and next some relevant resulting graphs are analyzed in detail. Afterwards a comparison of the results obtained by PV systems with south and east-west orientation with different inclinations is made.

As there are many variables that can be set in the model, the followings are selected to be constant in these examples:

- Irradiance → PVGIS (kW/m²)
- Load profile
- Threshold = 1200 kW
- PV specifications
 - Rated power = 500 kW_p
- Battery specifications
 - Type: lead-acid
 - Capacity = 300 kWh
 - SOC min = 20 %
 - SOC max = 100 %
 - Charge rate = 1/3 h⁻¹
 - Discharge rate = 2/3 h⁻¹

Only the season and the orientation and inclination of the PV system are varied because the main target of the present project is to decide whether the E-W orientation is advantageous for covering the peaks of the demand.

6.2.1 Results for Some Examples

In this first example, a simulation is run with January irradiance data and with an E-W PV system with a 15° of tilt angle.

The main results of the simulation are presented in the Figure 58.

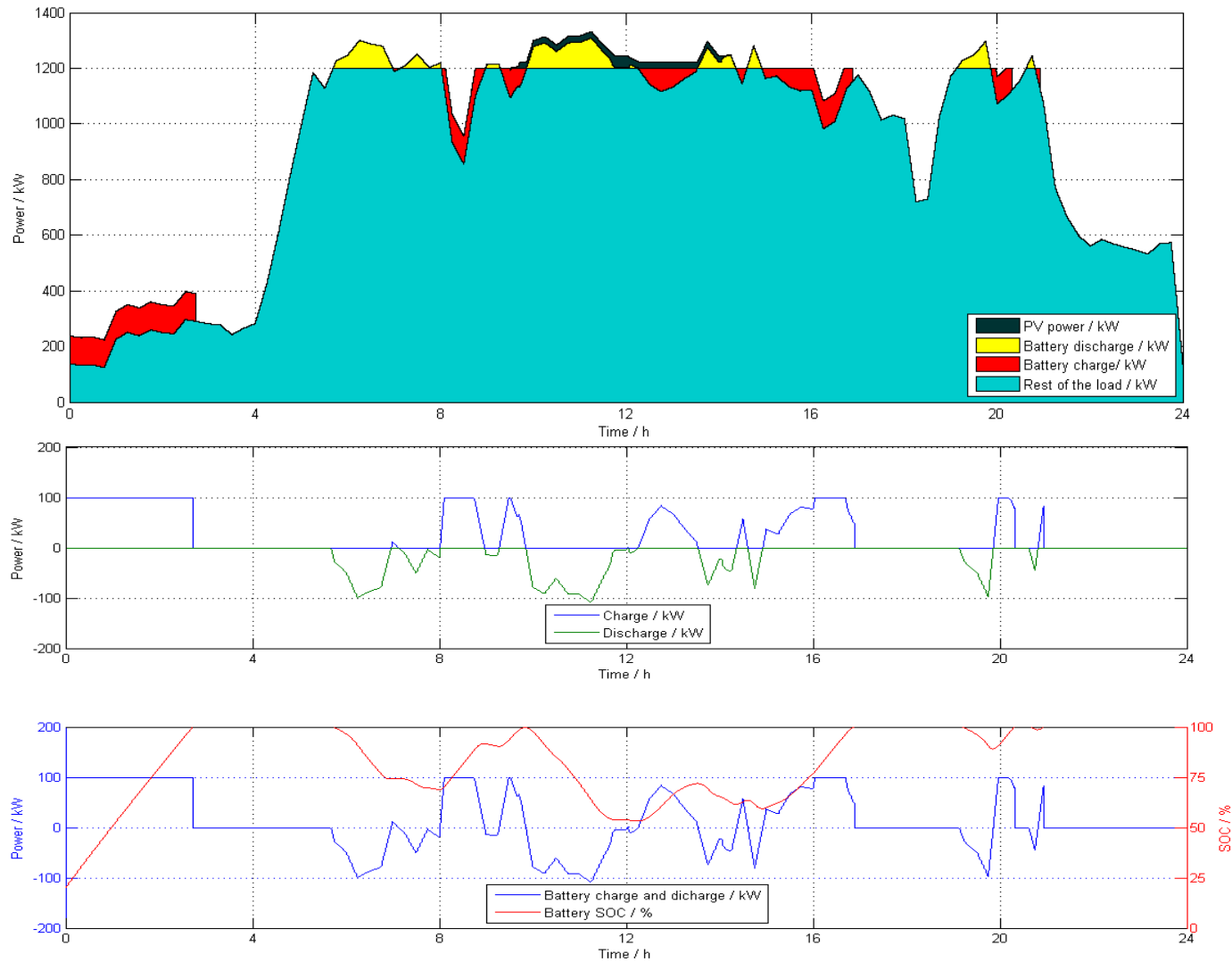


Figure 58: a) Load curve of a company and fractions covered by each component: 15° E-W PV system in January, battery and grid;
 b) Discharge (-) and charge (+) of the battery

In the Figure 58 it can be seen that the battery covers the peaks when necessary and the grid charges the battery if possible during the night and when there are valleys in the load after having subtracted all the PV power generated.

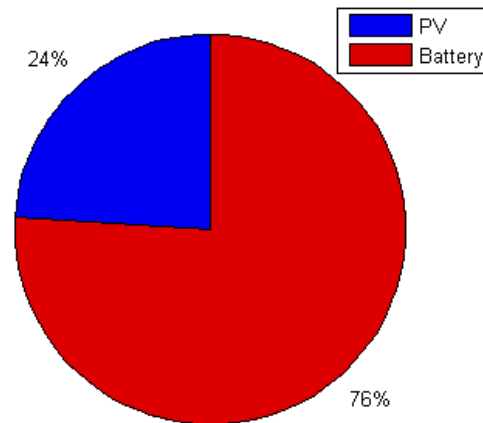


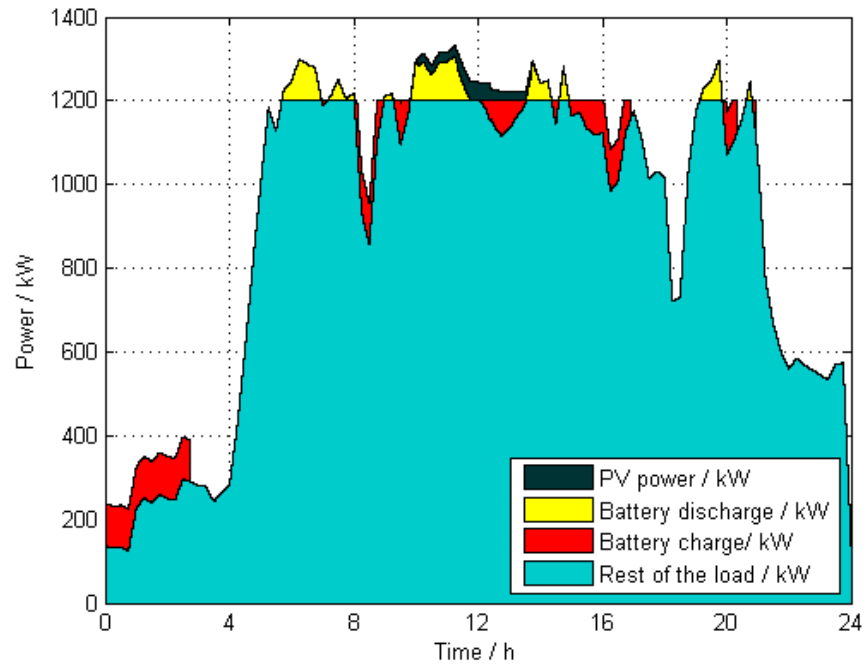
Figure 59: Percentage of the total power supplied above the grid threshold by each power source with a 15° E-W PV system in January

Even though January is a month with low irradiance levels, as the *grid power exceeding threshold* in the Figure 59 is zero, the goal of covering all peaks by the battery and the PV system has been reached.

Next the previous example is compared with another in which the PV system remains with the same characteristics (E-W with a 15° of tilt angle) but a sunnier season is chosen: July.

The main results of the simulation are presented in the Figure 60.

a) 15° E-W, January



b) 15° E-W, July

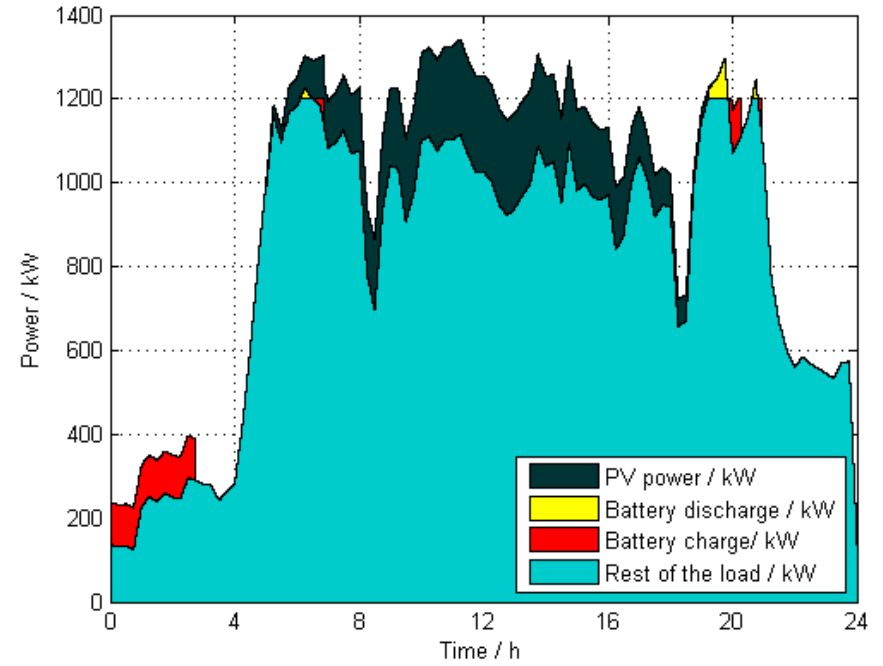


Figure 60: Comparison of the fractions of the load curve covered by each component (PV system, battery and grid) for a 15° E-W PV system in a) January and b) in July

From the Figure 60 an important conclusion can be inferred: the battery will mainly be used in the seasons with low radiation rates and, on the other hand, its support will be rarely required for the sunny seasons because the PV power is already covering the major part of the load peaks. In the case of a lead-acid battery, this way of operation over the year will not damage the battery as long as its state of charge is maintained high (around 95-100%) during the seasons of high radiance rates.

6.2.2 Analysis and Comparison of the Results

Twelve simulations are run for checking which orientation and inclination for the PV system is the optimum for making the most of the PV power generated. The south system is always set to 30° of tilt angle (because it is the optimum inclination in the latitude of Germany), but for E-W orientation with tilt angles of 15° and 25° will be checked.

The parameters are the same that the ones that were selected in the 6.2.1 section.

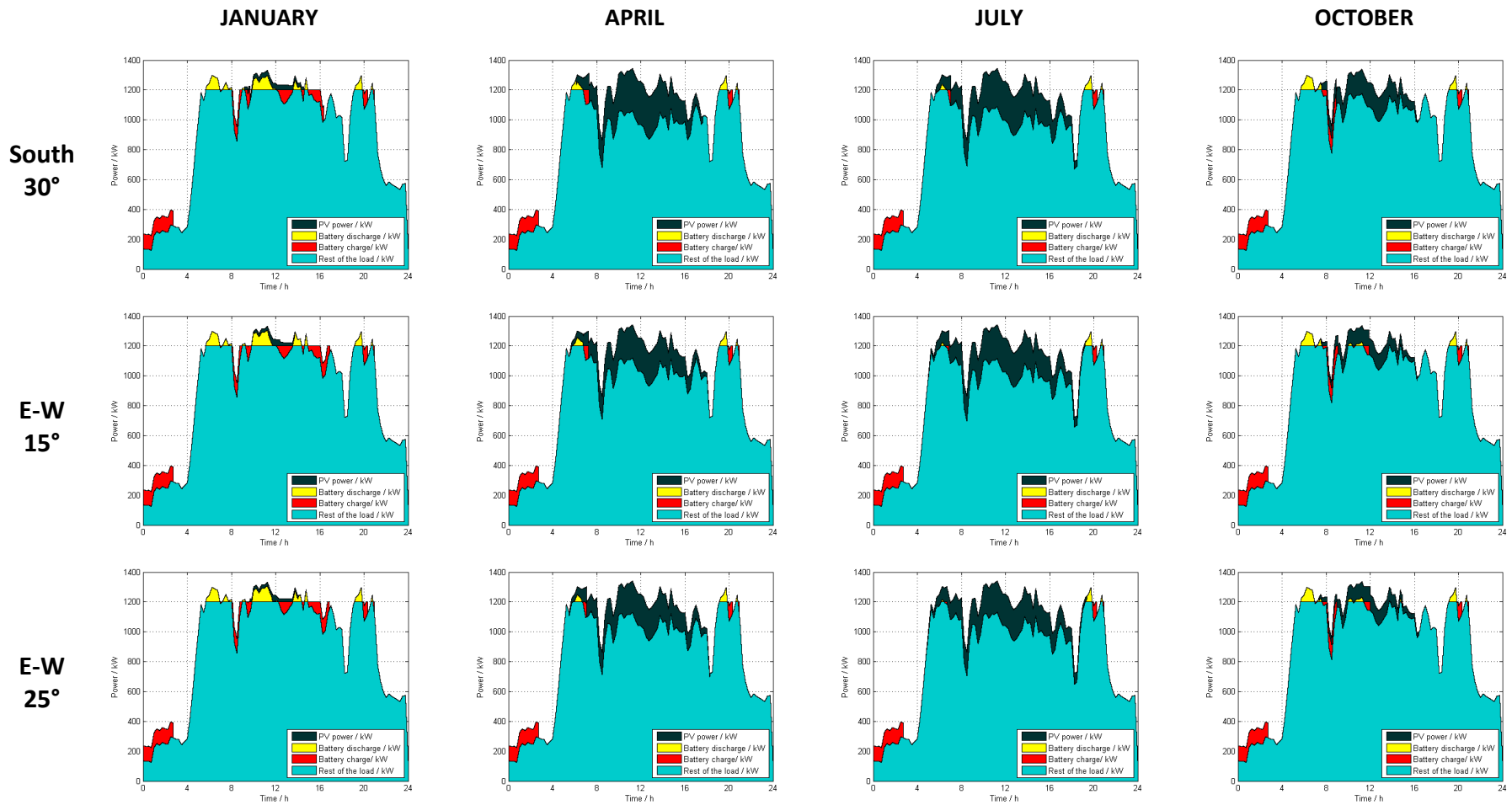


Figure 61: Comparison of the fractions of the load curve covered by each component (PV system, battery and grid) for different months and orientation and inclination for the PV system

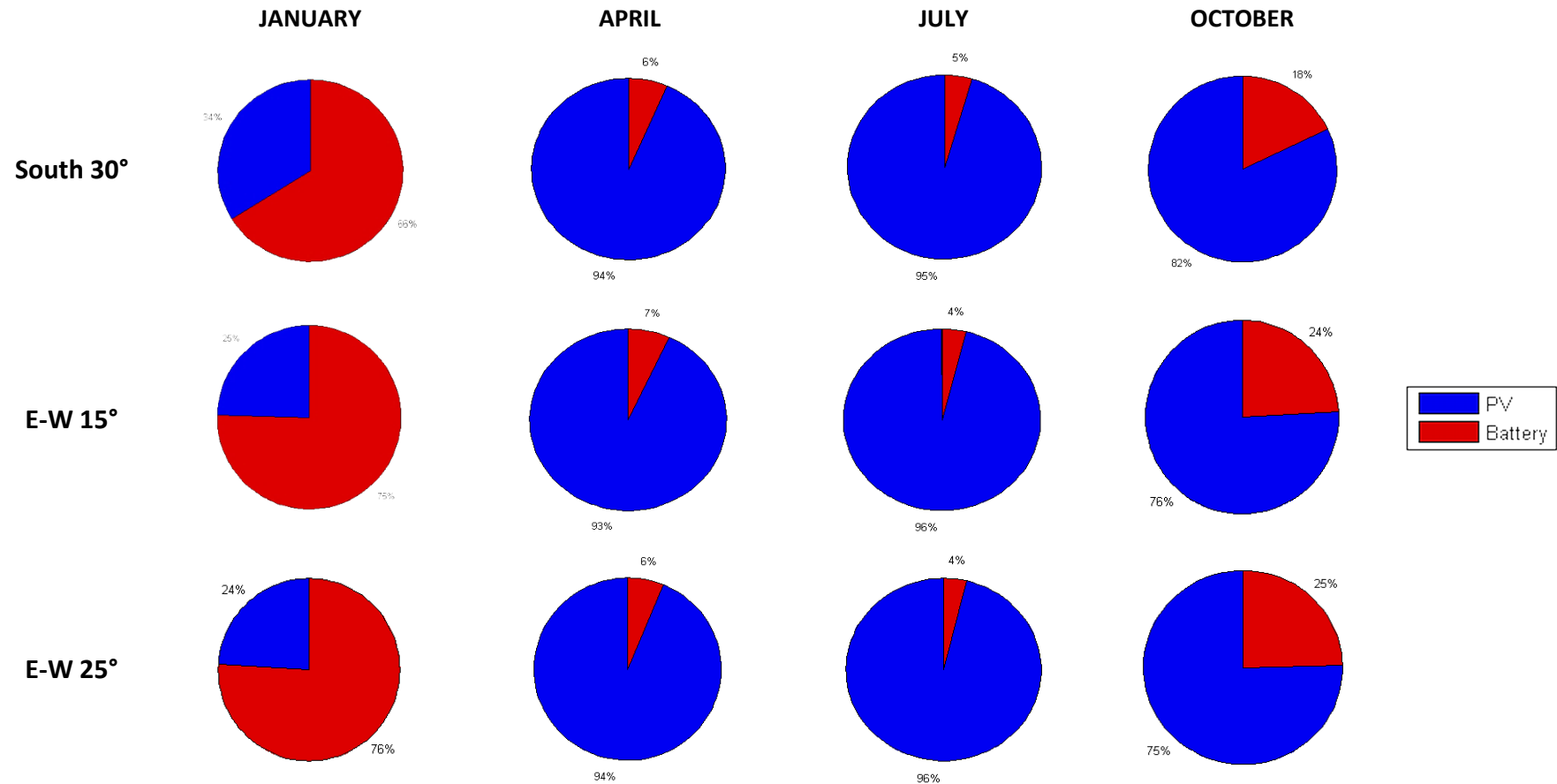


Figure 62: Comparison of the percentages of the total power supplied above the grid threshold by each power source for different months, orientations and inclinations for the PV system

Seeing the Figure 61, directly it is not easy to distinguish which orientation and inclination is the most adapted to the load curve, but it is confirmed again that the battery is mainly used in the seasons with low radiation rates and that its support is rarely required for the sunny seasons.

The Figure 62 shows clearer which components are covering which percentages of the peaks. It can be observed that a south orientated PV system is better adjusted to this specific load curve than an E-W system because the use of the PV power for the peaks is always higher. There is only one exception in July, where the south system uses 95% of the PV power and the east-west uses a slightly higher percentage, 96%. In a rougher analysis it can be seen that in the months of April and July the results are not so different for both orientations, but in January and October it is clearly better to have a south orientation. This may probably be because in April and July the sun is higher and there are more sunny hours (sunrise at 5:37 and sunset at 18:37 for April and sunrise at 4:22 and sunset at 19:52 for July) than in the rest of the simulated months (sunrise at 8:22 and sunset at 15:52 for January and sunrise at 7:07 and sunset at 17:07 for October).

So after looking at the Figure 61 and Figure 62, it can be said that for this specific load curve, for both orientations the results are very similar for the sunny seasons, and for the low irradiance seasons it is better to use a south orientation because the PV self-consumption is much higher.

To finish, after revising all the results the conclusion is that at least for this specific load curve there is not any significant advantage for using E-W instead of south orientated systems for covering the peaks of the demand. Nevertheless, for a demand with a midday peak the south orientation may be better and, on the other hand, for flatter load curve the E-W orientation may be more favorable.

7 Economic Considerations: South vs. E-W

In this chapter some critical reflections regarding the economic aspects of the south systems facing the E-W orientated PV systems are presented.

7.1 Energy

In this section the energy produced by the PV modules over one year is calculated by the Simulink model shown in Figure 48. A south system with 30° of inclination and an E-W system with 15° of inclination are simulated using the monthly average irradiance data from the PV-GIS database. Both installations have a rated capacity of 1 kW_p.

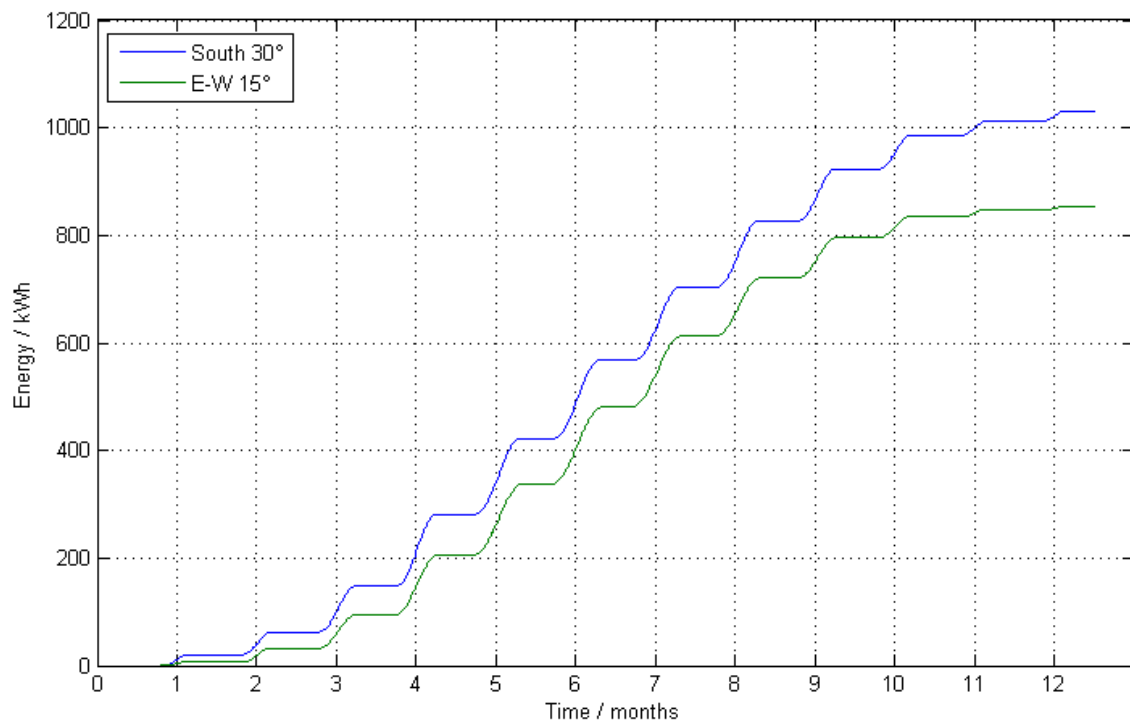


Figure 63: Comparison of the yearly energy produced by one PV installation of 1 kW_p rated capacity with different orientation and inclination: south 30° and E-W 15°

In theory, at the Osnabrück latitude, a 1 kW_p PV system with south orientation and 30° of inclination produces 900 kWh/ year [8]. In the Figure 63 it can be seen that the simulated PV system is in approximately in coincidence with this assumption, because the total energy generated annually by the south 30° system is 1031 kWh and by the E-W 15° system 853 kWh. Thus, the E-W system produces annually around the 83% of the total energy produced by a south system.

7.2 No Influence on the Maximum Grid Power Consumption

As explained in the section 6.1.3, the battery is the component that must assure the supply, independently of the solar irradiance, because this natural source is unpredictable. Therefore using a south or an E-W PV system will not affect the maximum grid consumption because as there may be days without nearly any irradiation, the consumer can only rely on the battery. Thus, a solar system – be it E-W or south oriented – can never be used to reliably reduce the maximum grid power consumption of a company.

7.3 Use of the Roof Area

Even though the structure costs of both installations are very similar [20], the use of the available roof area is much higher with the E-W modules. South-faced systems need gaps between the module rows, otherwise they shade each other and, on the other hand, with an E-W support structure the rooftop installed rated PV power can be almost doubled (see Figure 64).



Figure 64: South and E-W frameworks

Thus, for a given restricted roof area, the company can install the double rated power and raise the produced energy by a factor of x , with $x = 2 \cdot z$, with z being the energy reduction factor because of the E-W orientation, see subchapter 7.1.

With $z = 0.83$ or 83%, the produced energy on the roof would rise by a factor of $x = 1.66$ or 166% because of E-W. It must be kept in mind that in this case the investment would increase by a factor of 2.

7.4 More Solar Energy because of Broadened Curve

In this section, the possibility of enhancing an E-W PV capacity due to the broadening of its generation is explained and economically analysed.

Firstly, it must be known that the PV rated capacity installed must never exceed the load demand. Otherwise the exceeding solar power produced must be fed into the grid and sold at a lower price than the consumption price avoided, which results in an uneconomical inversion. In the

Figure 65 an appropriate and an excessive PV capacity for a certain load demand are presented.

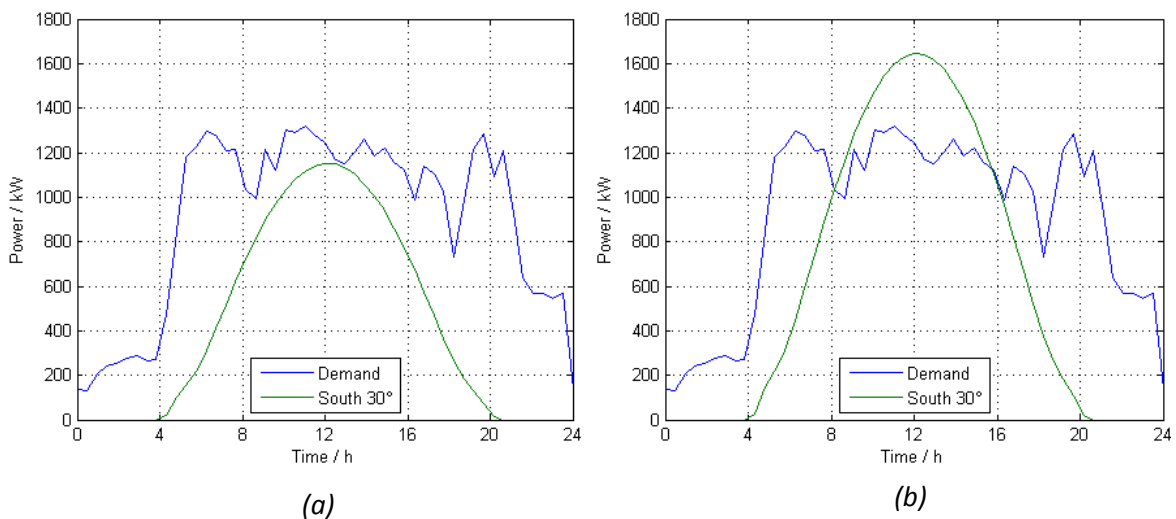


Figure 65: Load demand facing the real south 30° power generated:

a) PV system with an appropriate capacity; b) PV system with excessive capacity

After clarifying that, in this paragraph the expected performance of an E-W PV system facing the typical south system performance is explained. The initial idea was that the E-W system would broaden the generation curve significantly. As this generation curve would be lower as well, then this would allow the company to increase the E-W capacity. This idea is shown in the

Figure 66.

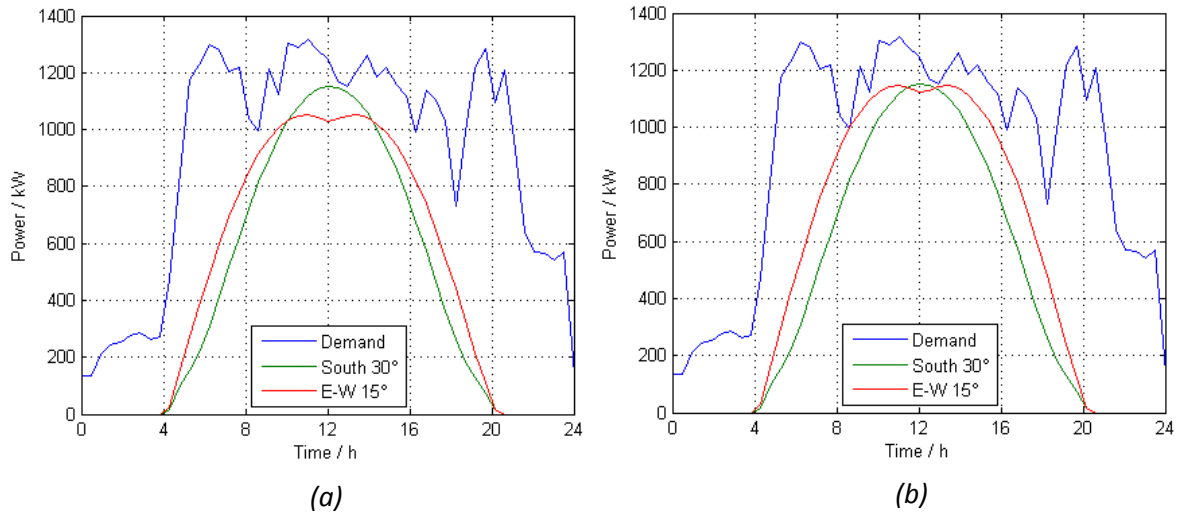


Figure 66: Load demand facing real south 30° and supposed EW 15° power generated:
a) PV systems with same capacity; b) Enhance of the EW capacity

Nevertheless the results (see

Figure 67) revealed something different: the broadening due to the E-W orientation is practically insignificant and when enhancing its capacity, both south and E-W generation curves have similar appearances. This analysis shows that the E-W installation of a PV field has only a very small effect on the expected broadening of the irradiance curve and therefore on the broadening of the produced solar power during the day.

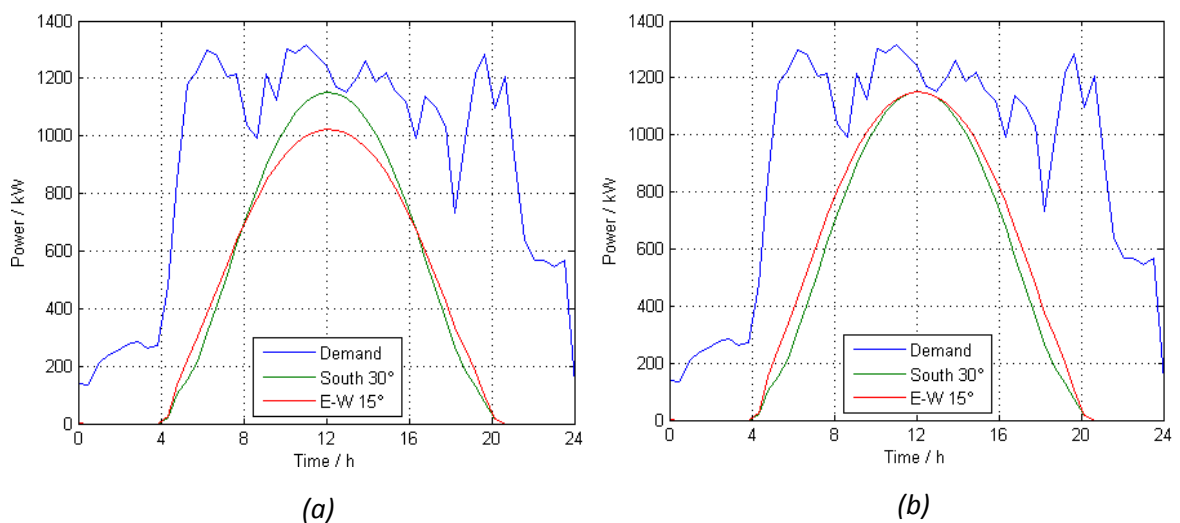


Figure 67: Load demand facing real south 30° and real EW 15° power generated:
a) PV systems with same capacity; b) Enhance of the EW capacity by 11%

On the other hand, as explained before, as the maximum power generated by an E-W PV is always lower than the generated by a south PV, the E-W PV would allow a company to increase its PV installed power. This increase must be calculated for the month of most irradiance, because the PV rated capacity installed must never exceed the load demand. This calculation was done in the subsection 4.1.3 and it showed that for achieving in July the output power of a 30° tilted south system with a 15° tilted E-W system, it would be necessary to install 11% more modules. Thus, this would rise the investment and the yearly produced solar energy with an increase factor of $w = 1.11$ or 111%.

So, instead of a south orientated PV system, the E-W system would produce the following energy:

$$E_{E-W} = E_{S,30} \cdot z \cdot w \quad \text{with}$$

z = E-W energy reduction factor

w = E-W capacity increase factor

In this simulation, with $z = 0.83$ (see subsection 7.1) and $w = 1.11$ (see subsection 4.1.3), the possible enhanced yearly energy would result in:

$$E_{E-W} = E_{S,30} \cdot 0.92, \text{ made possible by an investment of:}$$

$$I_{E-W} = I_{S,30} \cdot 1.11$$

In this sense, it is never economic to install an E-W PV field instead of a south PV, if the only advantage is the expected broadening of the curve.

7.5 Energy Policy

At the beginning it was supposed that an E-W installation would contribute to the power relief of the grid in two ways: Firstly by temporal balance because the production starts earlier in the morning and declines later at sunset without generating sharp peaks. Secondly through peak shaving thanks to the adaption of the PV to the load profile because in that way the utility does not have to face pyramid production.



Nevertheless the results show that as the broadening of the PV production curve is only 11%, the grids relieve effect would be around 11% as well. Therefore E-W PV will not be an important contribution to the relief of the electric grid in the future.

8 Conclusions and prospects

Conclusion

The adjustment of the simulated profiles from the supposed E-W PV system with the real demand profiles of the companies has been carried out successfully. Then, after analyzing the results they show that:

- 1) The yearly produced energy by a E-W system is 17% less than the produced by a south orientated system.
- 2) A solar system – be it E-W or south orientated – can never be used to reduce the maximum grid power consumption of a company.
- 3) On a restricted roof area, it is possible to install approximately the double PV capacity (rated power) in a 15° tilted E-W orientation, compared to a traditional 30° tilted south oriented system.
- 4) It is never economic to install an E-W PV field instead of a south PV, if the only advantage is the expected broadening of the curve.
- 5) The broadening of the E-W PV power generation will not be an important contribution to the relief of the electric grid in the future as the grid relieve effect is only around 11%

While making this report, an important threat was to choose proper software to simulate the proposed system, since it involves different components that were unlikely to be found in the same packet. Another drawback during this work was to find some information about E-W PV systems because they are a relatively new technology.

Prospects

Although south orientation is more ideal in terms of economy, E-W oriented PV systems can generate substantial earnings as well, and they allow making use of solar energy even if a roof has an E-W orientation or is flat with a restricted area. Nowadays the interest to mount PV systems on E-W roofs increases steadily and, moreover, due to the sharp drop in module prices increased demands for E-W plants are expected in the future.

References

- [1] AVI POWER. *Solar off-grid and grid-tied power packs* [online]. [Access at: July 2014]. Available at: <http://www.avi-products.com/AviSolarPowerPacks.aspx>
- [2] CHRISTIAN GLAIZE, Sylvie: *Lithium Batteries and other Electrochemical Storage Systems*, 2013
- [3] COUTURE, Toby D.; CORY, Karlynn; KREYCIK, Claire; WILLIAMS, Emily / *A Policymaker's Guide to Feed-in Tariff Policy Design*. Office of Energy Efficiency and Renewable Energy, July 2010
- [4] DEGNER, T.; ARNOLD, G.; BRAUN, M.; GEIBEL, D.; HECKMANN, W.; BRÜNDLINGER, R.; *Utility-scale PV systems: grid connection requirements, test procedures and European harmonization*. Institut für Solare Energieversorgungstechnik, Kassel, Germany
- [5] ELECTROPAEDIA: *Battery and energy technologies/ Battery performance characteristics* [online]. [Access at: July 2014]. Available at: <http://www.mpoweruk.com/performance.htm>
- [6] ENERGY TRANSITION: *The German Energiewende/ German PV feed-in tariffs* [online]. [Access at: July 2014]. Available at: <http://energytransition.de/2013/11/german-pv-feed-in-tariffs-to-drop/>
- [7] HK RE NET: *Solar Photovoltaic/ Electrical Properties of PV Modules* [online]. [Access at: July 2014]. Available at: http://re.emsd.gov.hk/english/solar/solar_ph/solar_ph_to.html
- [8] KUHNKE, Klaus. Personal communication, July 2014
- [9] MATHWORKS: *SimElectronics / Solar cell model* [online]. [Access at: July 2014]. Available at: <http://www.mathworks.com/help/physmod/elec/ref/solarcell.html>
- [10] MATHWORKS: *SimPowerSystems/ Battery model* [online]. [Access at: July 2014]. Available at: <http://www.mathworks.com/help/physmod/sps/powersys/ref/battery.html>
- [11] MOHEDANO MARTÍNEZ, Javier Bernabé: *Batteries in PV systems*. Wroclaw

University of Technology, 2001

- [12] NATIONAL GRID US: National grid Massachusetts / *Introduction to distributed generation* [online]. [Access at: July 2014]. Available at: http://www.nationalgridus.com/masselectric/business/energyeff/4_introduction.asp
- [13] QUASCHNING, Volker: *Regenerative Energiesysteme*, 2013
- [14] RE.JRC.EC.EUROPA: European Photovoltaic Geographical Information System from the Institute for Energy and Transport of the European Commission/ *Monthly global irradiation data* [online]. [Access at: July 2014]. Available at: <http://re.jrc.ec.europa.eu/pvgis/apps4/pvest.php>
- [15] RENEWABLES MADE IN GERMANY: dena (German Energy Agency) / *Photovoltaics regulatory framework* [online]. [Access at: July 2014]. Available at: <http://www.renewables-made-in-germany.com/en/renewables-made-in-germany-start/photovoltaics/photovoltaics/regulatory-framework.html>
- [16] SCHMIDT, Jan-David: *Evaluation of the impact of PV module orientation on grid operation*, 2nd International Workshop on integration of Solar Power Systems, Lisbon, 2012
- [17] THIEL, Hagen. Personal communication, May 2014
- [18] TRNSYS: [online]. [Access at: July 2014]. Available at: <http://www.trnsys.com/>
- [19] VOSS, M.; KUHNKE, K.: *Projektskizze: Ost-West-PV mit Speicher für Verbrauchsprofile von Betrieben*. Hochschule Osnabrück, 2012
- [20] VOSS, Mike. Personal communication, July 2014

Appendix

Appendix 1: Main controller program

```
function [load_minus_PV, Grid_battery_supply, Power_required] =  
    CONTROLLER(load, PV_power, SOC)  
  
% initialization of the variables  
Lad_minus_PV = 0;  
Grid_battery_supply = 0;  
Power_required = 0;  
  
% subtract all the PV power to the load  
load_minus_PV = load - PV_power;  
  
% calculate the power that needs to be covered by the battery if possible  
Power_required = load_minus_PV - Grid_threshold;  
  
% if needed and if load_minus_PV is lower than the Grid_threshold, charge  
the battery by the grid without overtaking the maximum charge power of  
the battery  
  
if SOC < SOC_max && load_minus_PV < Grid_threshold,  
    Grid_battery_supply = Grid_threshold - load_minus_PV;  
    if Grid_battery_supply > P_max_batt_charge,  
        Grid_battery_supply = P_max_batt_charge;  
    end  
else Grid_battery_supply = 0;  
end
```




Appendix 2: Secondary controller program

```
function [P_battery_in_out, Battery_discharge, Grid_exceeding_threshold]
    = Controller (Power_required, SOC, Grid_battery_supply)

%% this script controls the discharge power of the battery and calculates
the power that exceeds the threshold needed from the grid

% initialization of the variables

P_battery_discharge_and_protection = 0; % auxiliary variable
Grid_exceeding_threshold = 0;

% definition of the outputs

P_battery_in_out =
Grid_battery_supply - P_battery_discharge_and_protection;

switch Grid_battery_supply % this command operates as a switch
    case 0,
        Battery_discharge = P_battery_in_out;
    otherwise,
        Battery_discharge = 0;
end

%discharge control

if Power_required > 0,
%the battery is discharged if possible and it may be undercharged
    if SOC <= SOC_min,
        %the battery must be disconnected to avoid deep discharge
        P_battery_discharge_and_protection = Grid_battery_supply;
        % this assures that there is no power flow going in / out the
        battery;
        Grid_exceeding_threshold = Power_required;
    else
        % it is allowed to be discharge the battery
        if Power_required >= P_max_batt_discharge,
```



```
% the battery supplies its maximum discharge power and the rest is
covered by the grid
    P_battery_discharge_and_protection =
    P_max_batt_discharge + Grid_battery_supply;
    % in this way P_batt_in_out = -P_max_batt_discharge. In this
    case the P_max_batt_discharge variable is protecting the
    battery from overcharge
    Grid_exceeding_threshold = Power_required -
    P_max_batt_discharge;
else
    % the battery supplies the required power for covering the whole
    demand. There is no need or supplying power exceeding the
    threshold from the grid
    P_battery_discharge_and_protection = Power_required +
    Grid_battery_supply;
    Grid_exceeding_threshold = 0;
end
end
%charge

else
    %if Power_required <= 0, it is not needed battery discharge so the
    battery may be charged. It is impossible to overcharge the battery
    because Grid_battery_supply <= P_max_batt_charge; this condition was set
    within the "Main controller".
    Grid_exceeding_threshold = 0;
    P_battery_discharge_and_protection = 0;

end
```



Appendix 3: Graphical User Interface code

```
%Graphic User Interface for the initial variables
clear all;
button = 'Yes';

% run the simulation while the user wants it
while strcmp(button, 'Yes') == 1 % this function returns a 1 for
equality, or a 0 for inequality.

% set the font size for the menus
UIControl_FontSize_bak = get(0, 'DefaultUIControlFontSize');
set(0, 'DefaultUIControlFontSize', 14);

% Choose company load

run_load = questdlg('Do you want to run your ownn load excel file?', ...
    'Run load', 'Yes', 'No', 'No');
switch run_load

    case 'Yes', % import load file from the user
        h = msgbox(['Please save your load excel data in the current folder
            as "Load_company.xlsx".' 'The first column must show
            the time in seconds and the second the consumption in
            kW.'], 'Run load');
        waitfor (h);
        Load_company = xlsread('Load_company.xlsx', 'Matlab'); %import excel

        time_sim = inputdlg2 ('How much time do your selected data require?
            (in seconds)', 'Simulation time', 1);
        t_sim = str2double (time_sim{1});
        if isempty(time_sim) == 1,
            close = errordlg('Program interrupted', 'Error');
            waitfor(close); stop; end % close window

    case 'No', % run load file already included in the program
        r0 = menu2('Choose the company load for the
            simulation', 'Company 1', 'Company 2', 'Company 3');
        if r0 == 1, load('Load_company_1.mat');
```



```
elseif r0 == 2, load('Load_company_2.mat');
elseif r0 == 3, load('Load_company_3.mat');
else close = errordlg('Program interrupted','Error');
    waitfor(close); stop; end % close window

    otherwise
        close = errordlg('Program interrupted','Error');
        waitfor(close); stop; % close window
end

clear run_load time_sim r0 close;

%Choose irradiance data and PV orientation and inclination

r1 = menu2 ('The irradiance is the average irradiance for a month
(kW/m2). Which month would you like to simulate?', 'January', 'April',
'July', 'October');

r2 = menu2 ('Which orientation do you want for the PV system?', 'East-
west', 'South 30°');

if r2 == 1, r3 = menu2 ('Which inclination do you want for the east-west
PV system?', '15°', '20°', '25°', '30°'); end

if r1 == 1 && r2 == 1 && r3 == 1, load('Jan_Power_EastWest_15.mat');
PV_power = Jan_Power_EastWest_15; clear Jan_Power_EastWest_15; end
    .
    .
    .
if r1 == 4 && r2 == 2, load('Oct_Power_South_30.mat');
PV_power = Oct_Power_South_30; clear Oct_Power_South_30; end

clear r0 r1 r2 r3 UIControl_FontSize_bak; % delete variables

%Parameters of the system

answer = questdlg(['The default parameters of the system are the
following:' char(10)...
' ' char(10)...
'Grid consumption target:' char(10)...
```



```
' - Grid power threshold = 1200 kW' char(10)...
'Specifications of the PV system:' char(10)...
' - Rated power of the PV system = 500 kWp' char(10)...
'Specifications of the battery:' char(10)...
' - Capacity of the battery = 300 kWh' char(10)...
' - SOC* minimum for the battery = 20%' char(10)...
' - SOC* maximum for the battery = 100%' char(10)...
' - Charge rate = 1/3 h^-1' char(10)...
' - Discharge rate = 2/3 h^-1' char(10)...
' *SOC = State Of Charge of the battery' char(10)...
'Do you want to use the default values?' char(10)...
' ' char(10)], 'Parameters of the system','Yes','No','Yes');

waitfor(answer);

switch answer

    case 'Yes', % if answer = yes, run the default parameters

Grid_power_threshold = 1200;
Rated_capacity = 12.5;
SOC_min=20;
SOC_max=100;
P_max_batt_charge = 100; % this gives a charge rate = 1/3 h^-1
P_max_batt_discharge = 200; % this gives a discharge rate = 2/3 h^-1

    case 'No', % if answer = no, charge values chosen by the user

        % Grid power threshold
r4 = inputdlg2('Which power threshold (kW) do you want for this system?',
'Threshold power',1);

if isempty(r4) == 1, close = errordlg('Program interrupted','Error');
waitfor(close); stop; end % close window
Grid_power_threshold = str2double (r4{1});

while isnan(Grid_power_threshold)==1, %if answer NaN
    ok = msgbox ('Input data is not a number'); % warning
    waitfor (ok);
```



```
end

    % Rated power of the PV system
r5 = inputdlg('Rated power of the PV system (kWp)', 'PV system
specifications', 1);

if isempty(r5) == 1, close = errordlg('Program interrupted', 'Error');
waitfor(close); stop; end % close window
PV_capacity = str2double (r5{1});

    while isnan(PV_capacity)==1, %if answer NaN
        ok = msgbox ('Input data is not a number'); % warning
        waitfor (ok);
    end

    %Battery specifications
r6 = inputdlg({'Rated capacity (kWh)', 'SOC minimum (%)', 'SOC maximum
(%)', 'Charge rate (h^-1)', 'Discharge rate (h^-1)'}, 'Battery
specifications', 5);

if isempty(r6) == 1, close = errordlg('Program interrupted', 'Error');
waitfor(close); stop; end % close window
% Total_capacity(Wh) = Rated_capacity(Ah)*Unominal(V) and Unominal = 24V
Rated_capacity = str2double (r6{1})/24;
SOC_min = str2double (r6{2});
SOC_max = str2double (r6{3});
P_max_batt_charge = Rated_capacity*24*str2double (r6{4});
P_max_batt_discharge = Rated_capacity*24*str2double (r6{5});

    while isnan(SOC_max)==1 || isnan(P_max_batt_charge)==1 ||
isnan(P_max_batt_discharge)==1, %if any answer NaN
        ok = msgbox ('Some input data is not a number'); % warning
        waitfor (ok);
    end

    otherwise % if answer not y/n, the window must be closed

close = errordlg('Program interrupted', 'Error'); waitfor(close); stop;

end
```



```
clear answer ok r4 r5 r6 button; % delete variables
% run the simulation and put a timebar meanwhile
h = waitbar(0, 'Simulation running... (To abort process, press Ctrl+c)');
    t_sim = 86400; % 86400 seconds are equivalent to one day
    sim('PV_system', t_sim) % run simulation
close(h)

% show the graphs
h = msgbox('Next are presented the resulting graphs', 'Graphs');
waitfor (h);
    run ('PV_system_plot');
    run ('Battery_dis_charge_plot');
    run ('Power_exceeding_threshold_plot');
h = msgbox('Click Ok when you finish with the graphs', 'Graphs');
waitfor (h);
clear ans tout; % delete variables

% Save results
save_data = questdlg('Do you want to save the data?', ...
                    'Save Dialog', 'Yes', 'No', 'No');
switch save_data
    case 'Yes',
        h = msgbox('The file will be saved in the current folder as
                    "data_PV_system.mat"', 'Filename');
        %Save variables to 'data_PV_system.mat'
        filename = 'data_PV_system.mat';
        save (filename);
        waitfor (h);
end

% Quit or run another simulation
button = questdlg('Do you want to run another simulation?', ...
                  'Exit Dialog', 'Yes', 'No', 'No');
switch button
    case 'No',
        h = msgbox('Exiting program', 'Exit');
end

clear h button save_data t_sim; % delete variables
```