B-KUL-H05U3: Integrated Project in Energy

Design of a household PV & battery systems

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1 Introduction

2 Data Analysis for Solar Energy Optimization

2.1 Input data

The analysis of PV and battery systems across the various considered scenarios relies on two pivotal datasets, critical for the design and optimization of PV and battery storage solutions in residential contexts.

First, solar irradiance data is gathered using both unshaded and shaded pyranometers to accurately measure Global Horizontal Irradiance (GHI) and Diffuse Horizontal Irradiance (DHI), respectively. Additionally, this dataset incorporates temperature readings for PV panels situated on diverse roof types. Captured minutely throughout the entirety of 2018 by a meteorological measurement system at EnergyVille in Genk (50.99461°N, 5.53972°E), this dataset provides a detailed overview of the potential solar energy available for conversion to assess the performance of PV systems.

Second, the household load data reflects the electrical demand patterns (in kW) of Flemish households, with measurements taken every fifteen minutes, paralleling the solar data's timeframe. Derived from real-world consumption statistics, this dataset offers detailed insights into residential energy usage, crucial for tailoring PV and battery systems to meet specific household energy needs. Collectively, these datasets form the empirical bedrock of our study, enabling a detailed exploration of how solar energy potential, household energy consumption, and the efficiency of integrated PV and battery storage systems interact within a residential framework.

2.2 Data processing

VICTOR

2.3 Solar panel irradiance calculations

To calculate the power and energy flows within the system, the processed solar data is utilized to determine the effective irradiance on the solar panels, oriented in the considered directions and positioned at particular tilt angles. The total effective irradiance on a panel typically includes a direct, diffuse, and reflective component [1]. However, due to the absence of data and the minimal contribution of the reflective component for monofacial PV modules, this term is omitted from this analysis. This is shown in form

$$GHI = DHI + DNI \cdot cos(\theta_s) \tag{1}$$

3 System description and Component selection

3.1 System overview

A variety of configurations are available for photovoltaic (PV) systems, dependent upon the objectives of the installation and specified boundary conditions. Within the scope of this project, solely grid-connected systems are investigated, both with and without a battery storage system. A disconnected, or off-grid system, is excluded from the analysis. This stems from the fact that these are generally less favourable in comparison to grid-connected systems, if a sufficiently developed grid is available. This is due to the fact that off-grid systems possess finite storage capabilities and lack the capability to draw surplus electricity from, or supply electricity to, the grid. The two possible grid-connected configurations are illustrated by Figures 1 and 2 [2] [3].

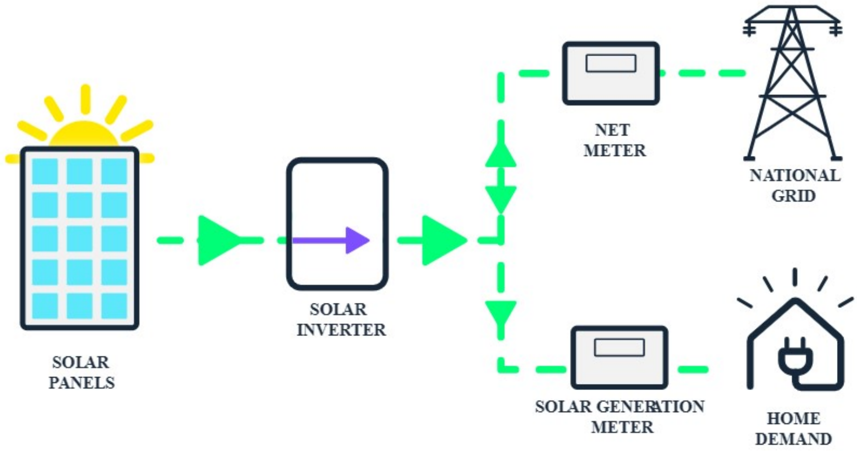

Figure 1: An on-grid solar system without batteries.

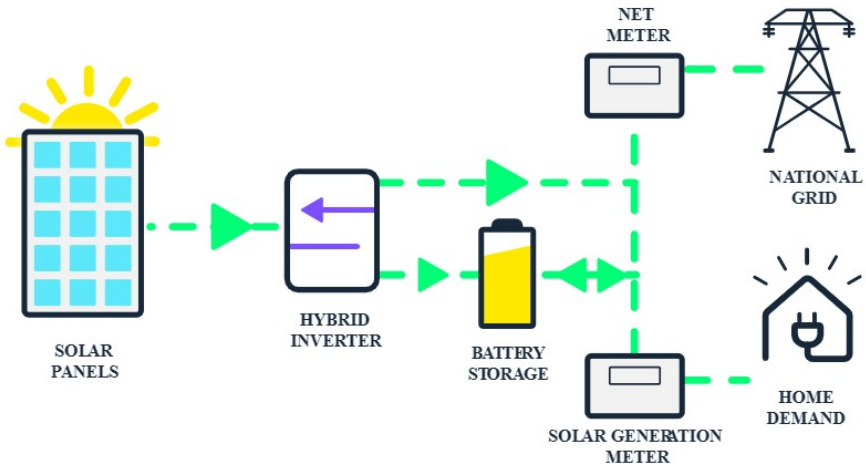

Figure 2: An on-grid solar system with batteries, also called a hybrid system.

In both installations, the solar panels, a certain type of inverter and the metering system constitute three key components, for which the inverter type is dependent on the system's topology. Moreover, a note has to be made regarding the metering systems shown on the figure. A solar and net meter is shown, however, both net and digital meters will be explained and analysed in detail. Furthermore, the second system utilises batteries for additional storage. In this configuration, a hybrid inverter is necessary. This inverter integrates the functionality of both a grid and battery converter, making it feasible to either store energy or convert it to alternating current. Each of these primary components will be discussed separately in following subsections. Other components such a wiring, fuses and disconnection switches will be discussed together [3] [4].

Subsequently, the model will need to optimise the installation and thus the combination of components. Ideally, this would be done over the entire collection of market available components suitable for the installation. However, due to practical considerations, a limited amount of well-chosen options for each component are considered here. Following sections discuss these options for the different components respectfully. Finally, Electrical Vehicles (EVs) will be discussed since these can have a significant impact on the demand profile.

3.2 Solar panels

For the solar panels, three of the market leading manufacturers are taken into consideration, being Canadian Solar, RECOM and Trina Solar. For each of these suppliers, two different types of panels are chosen which vary in coversion efficiency, max generated power, dimensions, price etc. This causes to have a market sample with substantial variation. All these datasheets are added in appendix.

3.3 Inverter

As said before, the choice of inverter is based on the configuration that is used. For the configuration in Figure 1, two different manufactures are chosen, namely SMA andd Victron Energy.

4 Power flow analysis

4.1 Theoretical analysis

The primary aim of the power flow analysis is to determine all power flows present in the system, from solar power input to consumption. This analysis is conducted for two distinct scenarios, namely without or with a battery system in place. In each case, the power flows are graphically presented in figures 3 and 4. Following subsections will step by step discuss the calculation of these flows and the efficiencies present [3].

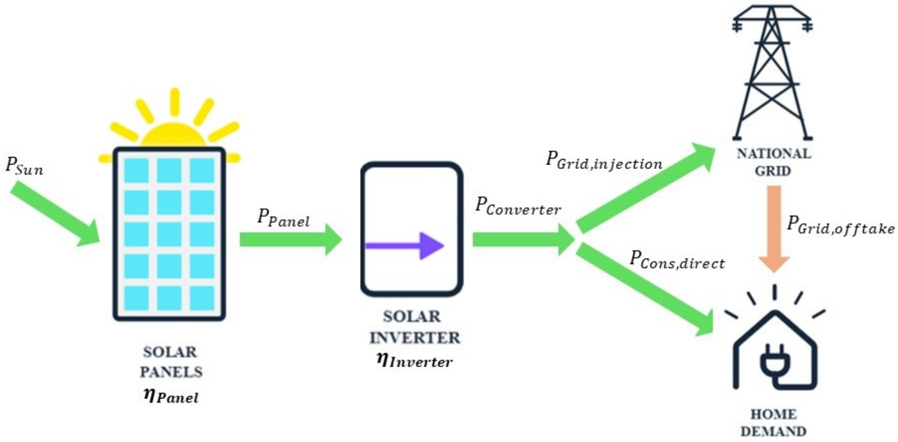

Figure 3: The power flows in a system without batteries [3].

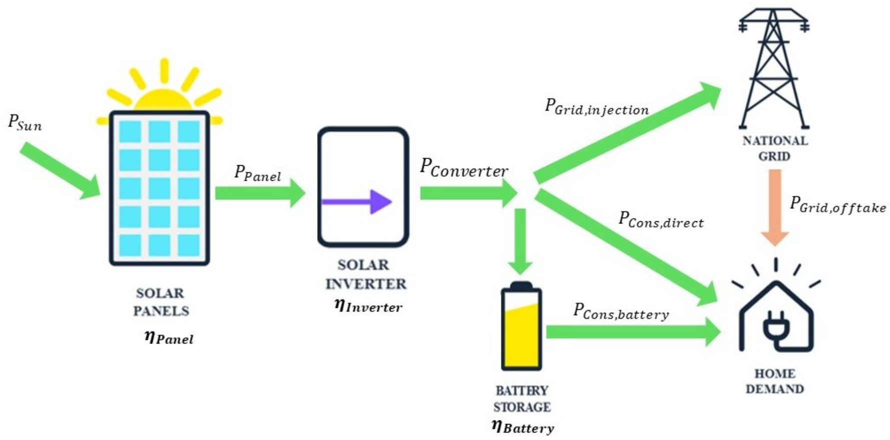

Figure 4: The power flows in a system with batteries [3].

4.1.1 Power PV panels

Section two delineates the computation of the Global Total Irradiance (GTI) on a inclined solar panel orientated towards a specific azimuth angle. Subsequently, to compute the total solar power P_{Sun} received, it is necessary to multiply this value by the quantity of solar panels n and the area A of each panel, as described by equation 2. The power supplied by the panels to the inverter P_{Panel} is determined by equation 3.

$$P_{Sun} = GTI \ . \ n \ . \ A \tag{2}$$

Table 1: Different factors contributing to the total solar panel effiency η_{Panel}[5].

	Value	Explanation
η_{Cell}	20.46-23%	The cell efficiency is given by the manufacturer and can thus be found in the respective datasheets.
η_{Shade}	100%	Assumption is made that not shade is present due to neigbouring buildings or trees.
$\eta_{Obstruct}$	100%	Assumption is made that no dirt or other materials are present on the panels. To achieve (near) this value, regular maintenance is necessary.
η_{Temp}	Formula 5	The influence of the temperature is a linear decreasing function of the panel temperature.
η_{Degrad}	Formula 6	The panel degradation can be approximated by a linear decreasing function of the time.

$$P_{Panel} = P_{Sun} \cdot \eta_{Panel} \tag{3}$$

The panel efficiency η_{Panel} is influenced by various factors, such as the cell efficiency, shading, obstructions, temperature, degradation etc. This is demonstrated in equation 4, for which each of these efficiencies are exemplified by table 1. However, the temperature and degradation dependencies will be further elucidated in the next paragraph. Furthermore, the assumption is made that each panel receives identical uniform irradiation at each time instance. Cloud coverage differences between panels is therefore neglected, since this influence is already present in the solar measurement data, as described by section two [5].

$$\eta_{Panel} = \eta_{Cell} \cdot \eta_{Shade} \cdot \eta_{Obstruct} \cdot \eta_{Temp} \cdot \eta_{Degrad} \tag{4}$$

As said, futher elaboration is necessary regarding both the temperature and degradation dependencies. Firstly, concerning the temperature-related efficiency, this can be approximated using equation 4 as was done by Evans [?]. In this equation, T_{ref} denotes the reference temperature, typically set at 25°C (or 298.15 K), T_c represents the cell temperature and β_{ref} signifies the temperature coefficient. The latter parameter is provided by the manufacturer and can be found in the appended data sheets [?].

$$\eta_{temp} = 1 \; - \; \beta_{ref} \, . \, (T_c \; - \; T_{ref}) \tag{5}$$

Secondly, regarding the influence of degradation, it is recognised that all panels experience a decrease in efficiency over time. The rate of efficiency decline depends on various factors which. However, an initial approximation can be made which states an average efficiency reduction of around O.5% per year. Mathmatically, this degradation factor η_{Degrad} per day t is given by equation 6. As visible, this factor remains proximal to unity and thus may be neglected in preliminary analysis [6].

$$\eta_{Degrad} = 1 \; - \; 0.005 \, . \, \frac{t}{365} \tag{6}$$

4.1.2 Inverter power

the inverter

4.1.3 Case 1

In case one, the solar inverter is solely responsible for converting the power from DC to AC. This conversion occurs with a certain efficiency $\eta_{Converter}$ as shown by equation 7. The value for the converter efficiency is given in the data sheet of the supplier. If the supplied power from the panels exceeds the inverter capacity, this conversion will be limited to this power $\P_{Converter,maximal}$

given in its respective data sheet.

$$P_{Converter} = \eta_{Converter} \cdot P_{Panel} \;\; if \; P_{Converter} < P_{Converter,maximal} \tag{7}$$

Following the conversion process, the power is either directly consumed by the connected loads or injected in the grid. In instances where the power generated by the panels exceeds the total instantaneous load, the surplus is injected into the grid. Conversely, if the generated power is insufficient to meet the total demand, additional power is drawn from the grid. These relations are shown by equations 8 and 9.

$$P_{Grid,injection} = P_{Converter} \;-\; P_{Cons,direct} \;\; if; \; P_{Converter} > P_{load} \tag{8}$$

$$P_{Grid,offtake} = P_{Load} \;-\; P_{Converter} \;\; if \; P_{Converter} < P_{Load} \tag{9}$$

4.1.4 Case 2

Case two is characterised by the presence of a Hybrid inverter that is capable of supplying AC and DC power to both consumption side and the battery system respectfully. This component is generally capable of managing the power supply to optimise consumption and charging behaviour to minimise the electricity cost. Therefore, as visible in figure 9, The power distribution after the inverter works differently in comparison to case one. However, as an approximation, formula 7 holds for the hybrid inverter as well, with its conversion efficiency given in the data sheets.

The power is primarily supplied to meet the loads and thus inverted from DC to AC. To approximate the optimisation behaviour of the hybrid inverter, following assumptions are made. In instances where the power generated by the panels exceeds the total instantaneous load, the hybrid inverter will charge the batteries to store energy. If this for some reason is unavailable, or the battery is full, excess energy is injected into the grid. Conversely, if the generated power is insufficient to meet the total demand, additional power is either drawn from the battery and/or from the grid, giving preference to the battery system if this is available and sufficient. It could be that the power discharge rate of the battery is too small in comparison to the needed remaining load, in that case the grid offtake will come to assistance. The battery system itself has a round trip efficiency given in the datasheets. These relations are expressed by equations xxx-xxx.

For the Battery system (if this battery system is not full yet and sufficient capacity is available, otherwise it is limited to its available charge capcity, discharge capacity or available system capacity) following equations hold.

$$P_{Battery,charge} = P_{Inverter} \;-\; P_{cons,direct} \;\; if \; P_{Inverter} < P_{Inverter,max} \; and \; P_{Inverter} > P_{cons,direct} \tag{10}$$

$$P_{Battery,charge} = P_{Inverter,max} \; if \; P_{inverter} - P_{cons,direct} > P_{Inverter,max} \tag{11}$$

$$P_{Battery,discharge} = P_{load} - P_{cons,direct} \; if \; P_{Battery,discharge} + P_{cons,direct} < P_{Load} \; P_{Battery,discharge} = P_{discharge,max} - \tag{12}$$

For the rest of the system:

$$P_{grid,injection} = P_{Inverter} - P_{Cons,direct} - P_{Battery,charge} \; if \; P_{Battery,charge} + P_{Cons,direct} < P_{Inverter} \tag{13}$$

$$P_{grid,offtake} = P_{load} - P_{Cons,direct} - P_{Battery,discharge} \; if \; P_{Battery,discharge} + P_{cons,direct} < P_{Inverter} \tag{14}$$

References

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[6] Simms, D, “Do solar panels lose efficiency over time?,” 2024.