Simple Free Use Simulation Software for Buildings with Photovoltaic System and Battery

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Abstract. The paper describes proposed techniques used for simple simulation of a hybrid energy system in a building. An interactive software tool is presented that can be downloaded and used for any purpose free of charge. Based on selected household electrical equipment, solar irradiance, PV system design and ESS parameters an annual simulation is made based on hourly time resolution. The outputs presented in charts as well as tables show the distribution of energy sources (grid, PV), the effect of ESS operation, self-sufficiency of PV system and its utilization of PV throughout the year. The simulation is real-time based so the system design can be easily manually optimized to achieve specific goals (e.g. specified self-sufficiency at minimal costs). As the simulation if based on Excel sheets, it can be easily accustomed by users with specific requirements.

1. Introduction

Photovoltaic (PV) installations together with energy storage systems (ESS) are becoming more popular to be used inside buildings. A proper design of a PV system with ESS is necessary to assure stable energy supply and optimal operation as well as cost savings. Simulations of hybrid systems with ESS are of primal importance in order to properly design and conceive such costly and sensitive systems.

Nowadays, there exist various types of software able to run simulations for PV systems. The software can be either general purpose (TRNSYS, Matlab, Mathematica…) or specific designed to run the energy simulations for renewable energy source (RES) integration. General purpose simulation software often provides sub-models for RES integration (developed by software provider or by 3rd parties) so that the user does not need to start from scratch. In this way TRNSYS offers a PV model based on one-diode model, models for microgrids for Matlab-Simulink were developed by University of Texas, etc. The main advantage is that this approach makes the user to get full control of the simulation – to define constrains, parameters and operation algorithm. The main disadvantage is that this software must be handled by users experienced in both – programming as well as RES system design.

On the other hand software designed to run simulations with RES can be easily handled by any persons trained for the specific software. The design and simulations can be easily and fast prepared, often in a few steps based on selecting components and parameters in a graphical user interface (GUI). The drawback is that for this type of software the functionality is often limited to perform rather common tasks – e.g. it might be impossible to control the energy fluxes based on innovative algorithms, integrate new or custom made elements etc. A comprehensive study comparing 19 software products to simulate operation of RES can be found in [1].
2. Integration of RES in buildings

The buildings sector, comprising both the residential and services sub-sectors, consumes 40% of the global energy usage and it is responsible for about 17% of the total direct energy-related to CO$_2$ emissions. A further increase of energy demand in buildings by almost 50% between 2010 and 2050 is expected [2]. To limit the impact on the environment, usage of traditional non-RES should be limited as much as possible. This can be done by combining both – energy saving measures and utilization of RES.

Electrical loads in a building can be supplied by various types of RES (PV, wind turbine, CHP or thermocouple powered by biomass, hydro…). For most of the cases using PV is the right option. There are less limitations on building location and its performance can be easily and reliably estimated. PV modules can be integrated or attached to the building and do not require extra space. In the last decade the R&D together with industry progress achieved a marked fall in PV system investment cost, mostly done by decrease of PV module prices. A net-price regression of 90% for a rooftop PV system can be observed over a period of last 27 years [3]. Last but not least, compared to the other RES types, PV shows high reliability and low service needs.

When integrating PV in the energy concept of a building, its energy needs have to be carefully analysed. This means to define (either by estimations based on loads and their utilization or by measurement) the building consumption profiles preferably in annual basis. If there are low seasonal variations a shorter period can be sufficient. Most of the building show a week based variation caused by occupation habits. In this way energy demand of an administrative building is usually lower during the weekends and state holidays.

To achieve a high local usability of PV energy, the PV installation should be designed in respect to this load profile. The PV peak power as well as the PV position (inclination and elevation) should be considered. If there is high need on energy during the evening, PV facing west or south-west should be preferred, to increase energy gain in wintertime higher inclination of PV modules can be beneficial.

Self-consumption of PV energy (local usability of PV energy) can be expressed as:

$$f_u = \frac{\int P_{PV} - \int |P_{GRID}(P_{GRID}<0)|}{\int P_{PV}}$$

(1)

where $P_{GRID}$ ($P_{GRID}<0$) means the grid power at intervals where $P_{GRID}$ is negative (feed-in the grid) and $P_{PV}$ is the current power generated by the PV source.

Similarly the index of self-sufficiency tells the ratio of autarky based on PV source,

$$f_s = \frac{\int P_{PV} - \int |P_{GRID}(P_{GRID}<0)|}{\int P_{LOAD}}$$

(2)

These indices play the major role when it comes to general evaluation of the contribution of PV source for the provider as well as economics. Local usage of PV energy is usually preferred as the building provider saves the energy budget. Grid injection is usually not much profitable or even prohibited.

When performing an energy simulation, the time resolution can be critical. Lower time resolution can make the simulation faster, but can possibly cause inaccurate or even wrong results. For a system without ESS time resolution of 1 min is necessary to achieve simulation error below 5%. A system equipped with ESS is much more robust, the input data-set can have a temporal resolution of 1 hour or even more according to the battery size [4]. Similar result are published by other studies [5, 6].

In case there is no ESS in the building grid, the situation of PV penetration is rather simple. At any time the excess energy is either injected to the grid or limited by PV system if the injection is prohibited. If the load exceeds the current PV power, the rest is taken from the grid.

For a system with ESS, the battery can be used to increase the self-consumption. There are several typical energy management concepts: store and immediately release discharge strategy maximizes PV energy self-usage, grid friendly enables load smoothing using peak shaving algorithm and energy market algorithm which simulates the behaviour of virtual power plant operator [7].
2.1. Topology of integration of PV source
There are two basic concepts how to integrate the PV system when using the ESS to the building grid, figure 1. First is based on AC coupling – the basic connection of connecting a PV source to the AC grid. This concept is recommended when the loads occur mostly on sunny hours. The other concept DC coupling connects the PV source to the battery system voltage and is recommended if loads during night are typical. Nevertheless both concepts are used and the decision depends on the system designer. In some solutions the PV generator is split and both concepts are used.

![Figure 1. Hybrid system topology – AC and DC coupling of PV generator](image)

3. Prepared model in Excel

3.1. Program appearance and behaviour
A simple model to perform annual simulation on hourly time resolution was implemented using Excel sheets. This program was chosen from several reasons: it is a common environment typically installed on PCs, the interface is simple, understandable and widely used. It enables effective work with data and its visualisation at the same time. The simulation file is divided into 4 basic sheets for user interaction (other for advanced parameter setting and performing simulations are initially hidden)

Sheet PVsystem defines the PV system parameters (module electrical and thermal parameters), PV generator layout, cable losses and inverter/charger parameters. It performs elementary checks of the PV generator to inverter configuration. For output the monthly irradiation on module plane and energy yield is presented (table and graphs).

Sheet HourlyMetoData gives the input for irradiance and ambient temperature to be used in simulations. Solar irradiance on module plane has to be used as the transition from horizontal to module place is computationally extensive (using e.g. Perez model) and is not integrated in the first versions.

PV cell operational temperature $T_{cell}$ is being derived from ambient temperature $T_{Air}$ and current irradiation $G$ by:

$$T_{cell} = T_{Air} + \frac{NOCT-20}{80} G$$

(3)

using nominal operational temperature (NOCT) that can be found in PV module datasheet (typically 45 °C).
Sheet **Load** is used to define the electrical load inside the building. This can be easily done by selecting various predefined appliances and their count. The appliances have initial value of typical power while operation and standby power and its typical usage is defined based on hourly fraction of operational time during weekdays and weekends. All these values can be altered if needed. A graph presenting the daily energy profile with hourly resolution for weekdays and weekends separately together with energy statistics is shown as an output.

Sheet **HybridSystem** is used to define the parameters for hybrid inverter and for the battery. The inverter parameters define its efficiencies for both directions of energy conversion (AC/DC) and its power limitations. For battery the efficiencies have to be defined together with capacity and state of charge limits.

When all the parameters in the above described sheets are defined, the result in **HybridSystem** sheet can be found. An **Overview table** shows the monthly statistical data of the system (energy generation, grid consumption, battery cycling, system losses...). Several graphs depict the monthly as well as annual system performance in term of energy sources, $f_a$, $f_i$, losses...

### 3.2. Simulation process

The main simulation time-step is one hour, so the sheet where it processes uses 8760 rows to cover a year, each representing state at hour $N$. The simulation starts with half-charged battery. SOC and grid interaction for row $N$ is being derived from excess energy at row $N$ and SOC at row $N-1$ according to figure 2. Firstly, the excess of energy is computed, if it is positive and the battery is not full, then the excess of energy will be stored in the battery. Otherwise, in the case that the battery gets fully charged, the rest is not locally utilised and it leads to grid injection or PV power limitation. If the excess power is negative, firstly the battery is used for the rest of energy needed to supply the loads. If the battery is empty (e.g. there is SOC limitation) the energy needed is covered from the grid. In the end the sum of energy taken from the grid, injected to the grid and used from PV is used to calculate the annual statistics.

![Excess energy diagram](image)

**Figure 2.** Layout of the technical containers and main building indicating the PV modules fields.

### 4. Simulation case study

This chapter shows an example of simulating the energy fluxes inside a typical family house. Common household electrical equipment is used, heating and hot water preparation is done by another energy source (gas, ...).
Considered loads are:

- lighting energy saving
- cooktop
- microwave oven
- kettle
- washing machine
- hair dryer
- notebook
- fridge/freezer

The load profile (figure 3) indicates 10.8 kWh on working day, 20.6 kWh on weekends and 4952 kWh annually. As additional energy source PV on the roof is used together with ESS. For a site in Prague a 4 kWp rooftop PV system facing south with inclination 45° indicates annual yield of 3840 kWh. ESS with capacity of 6 kWh was selected, cycling between 90 % and 10 %.

Based on the simulation the highest grid injection reaches 200 kWh in July and the self-consumption varies between 60 % and 95 % monthly within a year (figure 4). This indicates that maybe a higher battery capacity should be considered.

Figure 3. Daily load profile on a workday and weekend.

Figure 4. PV energy utilisation and self-consumption during the year.
Figure 5. Annual energy self-sufficiency and energy utilisation of PV system with ESS

Annually the system locally utilises 63% of PV energy, 31% is injected to grid. Using the PV source, the house is 47% self-sufficient. If no ESS was used, the local utilisation of PV energy as well as self-sufficiency would be much lower as it could be seen in figure 6.

Figure 6. Annual energy self-sufficiency and energy utilisation of PV system without ESS

5. Conclusion
Possible ways how to electrically connect a PV system with or without an ESS were presented in this paper. A simply tool for annual simulation developed in Excel was presented that can be used to adjust the parameters (PV power, battery size…) according to the expected results (self-sufficiency, local PV consumption) based on the building loads. This simple simulation approach shows fast results as it reacts in real time. Possible changes or adding of new features can be made by the user to this tool on a simple way. On the other hand for a detailed and more accurate purposes one should rather use a professional and mostly licensed version of a specific programs like those discussed in [1].

6. Simulation tool access
The software can be downloaded at https://github.com/UCEEB/HomeSim and used free of charge. Any comments and suggestions are welcomed.
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