

PHOTOVOLTAICS SYSTEMS

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GENERAL RELEVANCE

Photovoltaics (PV) energy is a major actor in the development of renewable energy. PV panels directly produce electricity under the sun irradiation. They can be installed on small and big buildings as well as on ground or on solar trackers at utility scale. For buildings, they used to be installed on roofs to maximize energy production over the year. Most of the PV owners used to sell the produced electricity injected into the grid at an interesting rate to compensate the owner PV system cost. Therefore, the buildings were consuming and buying electricity from the local grid distributor. Together with building energy retrofit and low consumption buildings, net zero energy or net energy positive buildings can be achieved.

Nowadays, PV systems are more and more optimized for self-consumption because of the lower offered price for injected electricity. The PV owners can have an initial subsidy and they are encouraged to consume their own produced electricity. At a more global scale, this strategy implicitly promotes the production of local energy with self-consumption strategies, completing the traditional grid production fed by electricity produced by centralized power plants such as nuclear, fossil energies, hydraulic, or wind energy. Depending on the building typology, PV can supply a major part of the electrical consumption of the building, including appliances as well as building systems such as HVAC and DHW. Self-consumption can be increased using electrochemical batteries. Self-consumption (fraction of self-consumed solar energy related to the total generation) and self-sufficiency (degree of total consumption covered by solar) are different objectives and sensitive to the time resolution of the data. An autark building would require the installation of costly seasonal storage solutions such as hydrogen storage.

Thanks to the dramatic drop of prices and emerging Building Integrated PV (BIPV) products on the market, BIPV are now also installed on roof and facades with an acceptable return on investment. Furthermore, facade production represents a non-negligible potential of renewable and local energy production in the built environment in dense urban areas.

As part of the roof or facade, BIPV panels are not superposed to the passive building elements but replace them by active elements producing electrical energy. The BIPV elements can combine energy production with one or more other building envelope functions such as water sealing, thermal, insulation, solar protection or any other function. Thanks to its multi-functionality with associated material savings, the resulting embodied energy for the building is theoretically lowered. BIPV integration is generally more aesthetic thanks to the choice of customized dimensions, colors and texture, transparency, material composition (glass/glass frameless, glass backskin, etc.). The main drawbacks of BIPV is lower efficiency due to size customization or reduced panel efficiency (from 5% up to 50% in worst cases with some color panels). BIPV elements are generally more expensive as price per watt for the initial investment. However, this can be compensated by the fact that more active surface can be generally covered on the building

thanks to size and aesthetic customization and the additional cost can be diluted by the saving of the building element itself. Moreover, the simultaneous installation of BIPV elements during the building construction or during energy retrofit of an existing building allows to drastically reduce the installation cost.

Any PV system is defined by installation parameters that will highly influence the annual energy production. The first set of parameters is linked with location latitude, longitude, and altitude. The closest local meteorological data must be considered for production calculation. Data are generally averaged values over several years, but can be time series as well. In addition, defining the short and the far field shading horizon can be very important in case of surrounding mountains, trees and other buildings. Then, the parameters linked with the integration of panels are set with orientation and inclination. Integration types free, on roof or façade. A good back ventilation of panel with a cooling effect has a positive influence on the yearly production.

PV TECHNOLOGIES

The PV technologies can be divided in two main categories. The first one, representing about 90% of the market share [1] is based on Silicon absorbing material (c-Si) with the two dominant products mono crystalline silicon (mono-Si) and polycrystalline (multi-Si). The second one is based on thin film technologies with a high potential of reducing embodied energy such as amorphous silicon (a-Si), Copper Indium Gallium Selenide (CIS/CIGS), Cadmium Telluride (CdTe) and organic PV cell (OPC). However, due their relative lower efficiency with a quantity of encapsulating material which remain unchanged, reducing the cost per watt as well as reaching the best environmental indicators such as GWP and CED per produced kWh over life time is very challenging. The thermal coefficient is lower, which is favorable in some cases with a higher specific energy production expressed in kWh per installed power kWp (kilowatt peak). Hetero-junction can be used to increase the efficiency, promising development are ongoing such as Perovskite and amorphous silicon on the silicon absorber.

Output power is given under standard conditions STC defined by sun spectra AM1.5 and direct sun irradiation 1000W/m^2 @ 20°C . Electrical characteristics IV curves with V_{oc} , I_{sc} resulting from cells in series and parallel also given at different illumination. The panel efficiency strongly depends on the active area with cells, the cell technology and the transparency of the front glass. The yearly production is also influenced by the temperature coefficient and the NOCT, both has to be the lowest as possible.

DC/AC-POWER CONVERSION

PV-Systems generate DC power at various voltage levels. Maximum power from the IV curve of panels is extracted by using a Maximum Power Point Tracker (MPPT). Depending of the consumer coupled the PV panels producer, the MPPT is integrated to DC/DC converters or in the DC/AC inverters. The consumer can be AC grid, AC loads of the building or a DC or AC electrochemical battery. The panels are generally connected in series before the conversion up to the maximum voltage and power of the converters. Panels in series are also limited to a maximum for security, in general 1000V as a standard. Alternatively, individual panels can coupled with micro-inverters (DC/AC) or power optimizer (DC/DC) with one MPPT per panel. This solution has the advantaged to overcome the problem of panel electrical mismatch due to fabrication differences or shadowing effects on a series of panel connected together, yearly production can therefore be higher.

RELEVANCE IN BUILDING COMPETITIONS & LIVING LABS

Sun powered houses are promoted by the Solar Decathlon competition (SD), and all PV technologies available on the market are to be represented. Depending on the rules of the competition, the maximum installed power is limited, to promote low consumption buildings. However, the limitation of installed power can be an obstacle to the installation of PV on façade because such installations cover larger surfaces with lower energy yield.

New PV technologies and non-certified products can be presented at the competition but with some limitations depending on the competition rules. Unless existing certification of the PV products, the voltage of the PV system can be limited for prototype. Case to case negotiations with SD organizers can be done for PV systems prototypes and proofs of performed reliability and security test must be shown. Developing prototypes in the frame work of the competition is interesting to promote emerging products, in particular in the BIPV market and high efficiency panels. PV coupled with direct heat energy generation are also of interest in SD competitions. This can be achieved by recovering heated air behind panels, or coupling Solar Thermal collectors (ST) with a circulating water. The last one is named as hybrids PVT panels. PVT panels produce heat as about 1/3 of standard ST panels and a slight improvement of the electrical energy yield is expected because of the water cooling effect of the PV cells thanks to circulating water. Typically, the PV output is considered in SD as part of the energy balance contest and associated sub-contests (100 to 120 points). No contest for the PV system performance itself exists up to now as all sub-contests address the balancing of generation and consumption combined.

CERTIFICATION, SECURITY, RELIABILITY

PV panels in series represent an electrocution hazard risk in case on defect of panel electrical insulation. The panel insulation must be guaranteed over the entire lifetime of the panels that is greater than 20 years. The certifications of PV product, IEC 61215 for multi-Si and 61646 for thin-film (a-Si, CIGS, CdTe), simulate ageing in outdoor conditions by doing test such as damp heat, humidity freeze and thermal cycling. Aesthetic appearance, panel performance and electrical insulation is checked after the tests. The IEC compliancy also includes mechanical and fire resistance tests. The tests give only an idea of the panel reliability which will depends on specific climate and integration conditions. Manufacturer generally offer panel warranty of 10 years for components defect and 80% of initial efficiency after 20 years in operating conditions. In the case of BIPV, typically in facade, the panel must be also complaint with the buildings rules.

Minimal requirements are necessary when installing panel prototype and pilot projects. If IEC certification cannot be provided, equivalent laboratory reliability tests must be shown and the components must be certified individually. The risk to install uncertified product is dramatic loss of PV system performance after few years, a change in the visible appearance as well as an electrocution

In case of R&D prototype, the voltage of the panel should be limited to 50V and must not be connected in series to limit the high risk of electrocution.

ENVIRONMENTAL IMPACT

The 'cradle to cradle' life cycle of PV should be considered, from the raw material of PV panels and balance of system (BOS: module supports, cabling, and power conditioning) until disposal and recycling of the installation. The environment indicator CED (primary energy use), CED_{nr} (no renewable energy use in MJ) and GWP (Gas Warming Potential in $kgCO_{2eq}$) can be expressed per m^2 , or per kW_p by taking

into account the panel efficiency. The embodied energy can be obtained from data base such as ecoinvent (see table 1) as well as study report [3].

Table 1: Environmental indicator of a 3kWp installation in Switzerland per kWp, 2015

Slanted-roof installation, Laminated, Integrated.	<i>GWP</i> [kgCO _{2eq} /kWp]	<i>CED</i> [MJ _{eq} /kWp] / [kWh/kWp]	<i>CED_{nr}</i> [MJ _{eq} /kWp] / [kWh/kWp]
Multi-Si, $\eta_{STC}=15.1\%$	1847	32'070 / 8'908)	27'302/ 7'584
CdTe , $\eta_{STC}=13.5\%$	1350	21'953 / 6'098	20'278 / 5'633

The impact factors of (BI)PV per kWh or produced energy is finally evaluated on the basis of the embodied energies and the predictable energy generation over their entire lifetime of maximum 30 years. Therefore, for a given technology, the environmental indicators will be reduced by installation with high yearly production strongly influenced by installation parameters. Typical energy payback time lower than two years can be achieved at Mid European conditions with photovoltaics (standard installations), and it can be demonstrated that installing PV on building reduces the carbon footprint [4]. Note that coupling PV with storage systems to increase self-consumption has the consequence to increase the total embodied energy. Therefore self-consumption strategies such as multi-oriented façade (see Figure 1), time shifting of loads with suitable algorithms and coupling PV with building systems should be promoted.

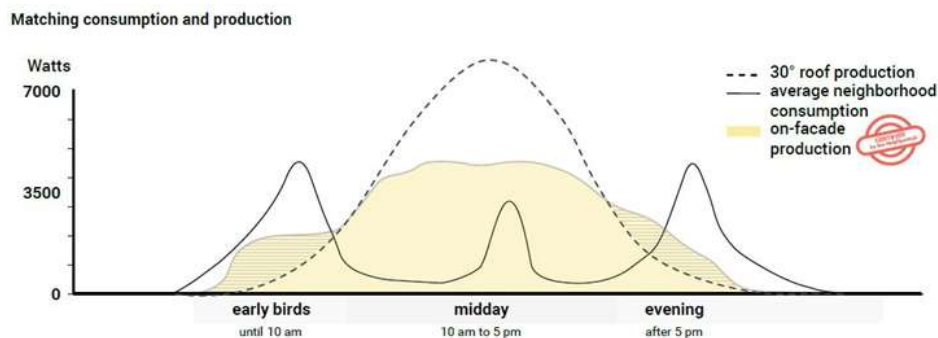


Figure 1: Strategy of a multi-oriented south, west and east facades to optimize self-consumption.

Source: Swiss Living challenge [5], DOE US solar decathlon 2017 Denver Colorado.

SIMULATION & MONITORING

Commercial software such as PVSyst (CH) or Polysun (CH) and general building planning such as DesignBuilder (US) can calculate energy production on a yearly, monthly and hourly basis. The two last software are able to calculate the coupling with building systems, which is a strong advantage when optimizing the self-consumption. These tools are used for the planning phase of the building before the installation; it also includes guide wizards for the dimensioning of the PV systems.

After installation, the PV system under operation can be monitored with details using the Inverters web portals or solar Datalogger such as meteocontrol or solarlog commercial products. Simple energy counters can be used alternatively without inverter's detailed measurements. The comparison between the yearly production and the production simulations of planning phase is the minimum, check but real time comparison can be done if weather historical data are available.

POST PROCESSING OF RESULTS FROM SIMULATION & MONITORING

The performance of the PV system is given by the performance ratio (PR , see norm IEC EN 612724) of system as follows:

$$PR = \frac{\text{Measured Production (kWh)(AC)}}{\text{Irradiation on panel } \left(\frac{\text{kWh}}{\text{m}^2}\right) \times A \times \eta_{STC}(DC)}$$

Unlike specific energy production indicator, expressed in (kWh/kWp/year), PR gives the performance of the installation independently of the orientation, inclination of the panel and weather conditions. PR values ranges from 0.7 to 0.9 with good system quality. PR includes all losses: inverter, temperature, DC cables, AC cables, panel mismatch, shadings, losses at weak radiation, losses due to dust, snow, ageing etc. [2]. In Figure 2, simulation and monitoring results from a 435 kW_p installation near Fribourg are graphically shown. The installation has 361 kW_p on roof (5° inclination) and 74 kW_p on south façade. The PR of the installation is 0.78.

For a detailed PV system analysis and diagnostic, the hourly simulations can be compared with the real measured production : lower efficiency at low illumination can be caused by inverter threshold or cracks in panels, or lower efficiency at high illumination can be caused by serial resistance in panels or inverter power clipping. Final diagnostic will be provided by checking the hardware (visually, with the help of infrared camera for hot spots...) and measuring electrical characteristics (V_{oc} , I_{sc} , IV curves) of panels and strings directly on the installation site.

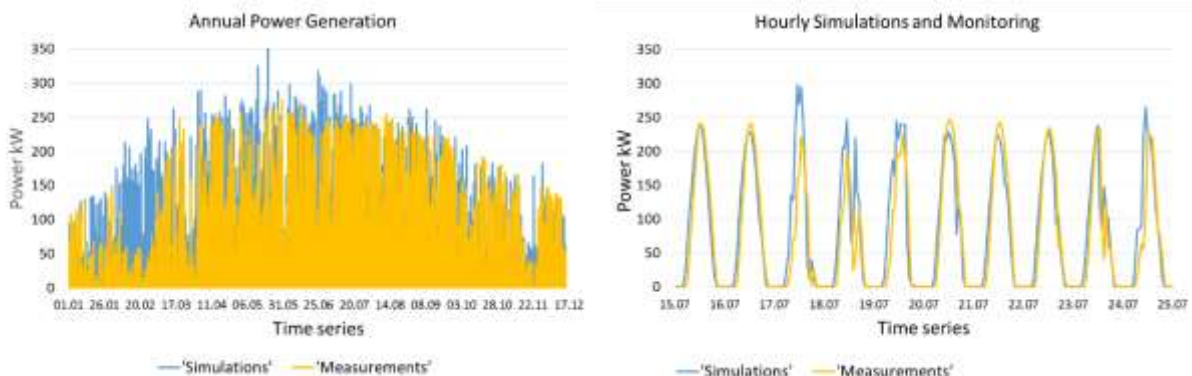


Figure 2: (Left) Annual Power Generation 2013 of a 435 kW_p Solar Power Plant in Western Switzerland. (Right) Hourly simulations and monitoring in clear sky conditions during summer.

FURTHER READING

- [1] Fraunhofer Institute for Solar Energy Systems ISE, (<http://www.ise.fraunhofer.de/de/downloads/pdf-files/aktuelles/photovoltaics-report-in-englischer-sprache.pdf>); 2019.
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- [3] IEA International Energy Agency, "Life cycle Assessment of Future Photovoltaic Electricity Production form Residential-scale Systems Operated in Europe", Report IEA-PVPS T12-05:2015, IEA-PVPS Task 12, Subtask 2.0, March 2015, R Frischnecht, René Itten, F Wyss
- [4] D. Vuarnoz, S. Cozza, T. Jusselme, G. Magnin, T. Schafer, P. Couty, E.L. Niederhauser, « Integrating hourly life-cycle energy and carbon emissions of energy supply in buildings », Sustainable Cities and Society, Volume 43, November 2018, Pages 305-316,

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