# Simulation of on-site Consumption for Building Integrated Photovoltaics (BIPV)

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## Abstract

In future the economy operation of a photovoltaic system is not any more depending on subsidies but on clever business models. One of the obvious solution with decentralized photovoltaic power plants is to use the energy where it is generated and therefore reduce grid interaction as well as conduction losses. Economically on-site consumption of locally produced energy reduces energy and grid use costs.

The paper illustrates the simulation of on-site consumption for prosumers (producer and consumer) with building integrated photovoltaics (façade systems). The input for the simulation software are meteorological data (temperature and radiation) with a resolution of 1 hour to calculate energy gain and load profiles characterising the consumer. The output is the proportion of the on-site energy consumption compared to the overall production and the degree of self-sufficiency.

For reliable results the load- and production profile of the prosumer must be predicted with a high temporal resolution. The applied method of load prediction is compared with measured load values of two given objects to verify the simulated results.

In a second section the simulation method is applied to simulate self-sufficiency of a residential and a school building. The influence of the building integrated photovoltaic (BIPV) orientation on self-sufficiency is determined for two given objects.

Finally, the optimal orientation of BIPV for self-sufficiency is obtained for the two investigated building types. This demonstrates that by proper selection of the building surfaces for BIPV an optimal on-site consumption and self-sufficiency can be reached.

Keywords: On-site Consumption, Load Profile Prediction, Energy Simulation, Building Integrated Photovoltaics, Prosumer

# 1. Concept and Definitions

## 1.1 Concept

The electrical energy fees on the market are ever declining while the feed-in tariff promoted by the Swiss government is gradually fading out. Therefore small decentralized energy producers need to find new return-on-investment strategies.

The previous concept was economically simple for the producer but not very smart on a larger scale. The energy was produced and sold on best conditions (noon in summer) not caring about where and at what time it can be used. On days with very high radiation this caused a price collapse on the energy markets and partially overloaded the distribution network.

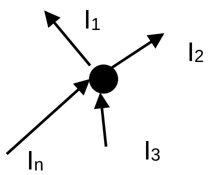
The new, smart concept should be: producing the energy when it is needed or even shift the load to the time when there is high energy production. It could be even worth thinking about storing the energy for the time with no production, which shall not be part of this documentation. The second part of this smart new concept is to replace standard parts of the building skin with high quality, energy producing components. By replacing parts of the building skin with high quality photovoltaic module synergy of the materials can be used to reduce construction costs and achieve very low energy production prices.

The question now is: which parts of the building are ideal to produce energy under this new aspects? To answer this question a simulation concept was developed to simulate different oriented solar power plants on building with various energy consuming characteristics. For this documentation a residential and a school building were investigated.

## 1.2 Definitions

### 1.2.1 On- Site Consumption

On-site energy consumption is based on the Kirchhoff's current law based on electro physical principles. The law implies that in any electrical node the algebraic sum of all currents is equal to zero.




$$\sum_{x=1}^{n} I_x = 0$$

Figure 1: Principle of the Kirchhoff's current law

Applied to an on-site consumption photovoltaic systems the energy meter is located between the node and the public grid. The electrical consumers (light, washing machine, heaters…) represent current sinks (positive, inward current flow). The photovoltaic power production plant equals to a current source (negative, outward current flow). The public grid can be simplified to an optimal voltage source which supplies or sinks any current that is requested.

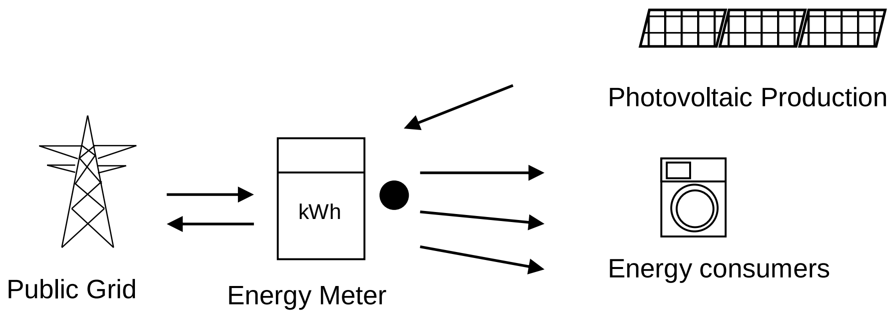



Figure 2: Principle of on- site consumption measurement

Due to this physical law on-site consumption is happening any time when energy production and consumption are overlapping no matter where the energy meter is situated. The placement of the energy meter is defined by the required energy values to calculate the cash flow between the different actors (energy supplier, producer and consumer).

### 1.2.2 Self-sufficiency

Self-sufficiency is defined by comparing the produced and the consumed energy ignoring any time factor between production and consumption. The electrical distribution network in this case acts as a temporary energy storage tank. To calculate the self-sufficiency the energy consumed $(E_c)$is divided by the produced energy $(E_p)$ over a certain period of time. Because of the seasonal fluctuations of production and consumption the time period must be at least one year [3]:

| | |
|---|---|
| $self\ sufficiency\ [\%] = \frac{E_p\ [kWh]}{E_c\ [kWh]}$ | Equation 1 |

This factor is used for economic considerations of the ecological added value. The certificates of ecological added values are traded without dependency of the time factor.

### 1.2.3 Self-consumption index (SCI)

Self-consumption is defined by how much of the produced energy is directly consumed on- site without using the electrical distribution network.

For calculating the self-consumption index the synchronicity of production and consumption must be considered. This can only be achieved with a good time resolution of the compared energy profiles (sampled values of production $(E_p(t_x))$ and consumption$(E_c(t_x))$). First the energy that cannot be used on-site (surplus $(E_o)$) is calculated, equation 2. To get the on-site consumed energy $(E_{on\ site})$ the surplus is simply subtracted from the annual produced energy, equation 3. To get the self-consumption index this value is divided by the overall energy production of the considered period [3], equation 4.

| | |
|---|---|
| $E_o = \int_0^{1\ year} \frac{(E_p(t_x) - E_c(t_x)) - \lvert E_p(t_x) - E_c(t_x)\rvert}{2}$ | Equation 2 |
| $E_{on\ site}\ [kWh] = E_p\ [kWh] - E_o\ [kWh]$ | Equation 3 |
| $self\ consumption\ index\ [\%] = SCI = \frac{E_{on\ site}\ [kWh]}{E_p\ [kWh]}$ | Equation 4 |

The self-consumption index respectively the on-site consumed energy is important for economic calculations.

### 1.2.4 Autarchy

The autarchy is the definition of how much of the consumed energy can be directly produced and consumed on-side. With an autarchy of 100% the electrical distribution grid is only required to sell the energy overflow but not to supply the consumers. To calculate the autarchy the on-site consumed energy, that was calculated before is divided by the energy consumption, equation 5.

| | |
|---|---|
| $autarchy\ index\ [\%] = \frac{E_{on\ site}\ [kWh]}{E_c\ [kWh]}$ | Equation 5 |

#### 1.2.5 On-site consumption performance (OCP)

To compare the different simulation results a new performance value, the on- site consumption performance, is introduced. The Power output of a solar cell or plant is usually given for standard test conditions (1'000W/$m^2$ solar radiation, 25° Module temperature, air mass index 1.5) operated in the maximum power point (MPP). The unit of this power is normally indicated in Wp. The "p" for peak indicates that it is a peak power under laboratory conditions that is mostly not achieved in normal operation. With this power value different types of modules can be easily compared because the energy yield is directly proportional to the installed power in kWp [2]. This makes the value very useful for normalizing figures (for example costs in CHF/kWp).

By dividing the on-site consumed energy ($E_{on\,site}$ ) by the installed peak power (P) the performance of solar plants with different orientations and power on different buildings can be easily compared regarding the on-site consumption, equation 6.

| | |
|---|---|
| $On - site\ consumption\ performance\ \ [kWh/kWp] = OCP = \frac{E_{on\,site}\ [kWh]}{P\ [kWp]}$ | Equation 6 |

# 2. Description of simulation algorithm

## 2.1 Load prediction

#### 2.1.1 Concept

For most of the buildings there is only insufficient data on energy loads and consumption available. For new projects the estimation of the energy profile is even more difficult because there are no consumption data available. Hence, the following estimations were made. For the two investigated building types different existing methods to generate the load profiles were applied and the results of each predicted load profile were compared with a realistic building where measured load profile data was available. The generated load profiles are not very precise and specific regarding actually installed consumers, but distribute the annual energy demand statistically over the defined time steps.

#### 2.1.2 Residential building

The load profile for residential building is simulated with the method of Coquoz [1] as follows:

1) Computing of appliances' hourly electricity need for six type days, using time distribution of appliances use per hour and appliances share of total household's electricity consumption over a year
2) Computing standard load profile
3) Computing of appliances' hourly share of household electricity for the six type days
4) Allocation of weekdays and season days
5) Smoothing of seasonal distribution
6) Computing of the synthetic demand profile
7) Alternative demand functions for some appliances (not required)

The following six day types are used:

Summer: Monday-Friday, Saturday, Sunday
Winter: Monday-Friday, Saturday, Sunday

Coquoz applies hourly usage distribution for 6 different day type directly from Prior [4].

The advantage of this method is that the energy is not only distributed in time space but also between different device groups (fridge, freezer, heating, hot water, cocking, dish washing, washing, drying, entertainment and others). The additional information's are useful to optimize on- site consumption in a next step.

#### 2.1.3 Office/ School building

For office buildings the definition of a standard load profile is more complex because of the wide range of different consumer profiles.

There is a definition of at least eight standard load profiles for industry and office buildings which were originally developed by VDEW (German electricity association) which is now merged to the BDEW (association of the German energy and water industries).

| Load profile | Description |
|---|---|
| G0 | General industries |
| G1 | Industries on general workdays (8:00 – 18:00) |
| G2 | Industries with high or mainly consumption in evening hours |
| G3 | Continuous industries |
| G4 | Stores / Hairdresser |
| G5 | Bakery |
| G6 | Weekend industries |
| G7 | Mobile radio station |

Table 1: VDEW / BDEW standard load profiles for industries [5]

The free available load profiles form Stadtwerk Unna from 2002 were used to generate a load profile for the simulation.

Instead of smoothing the load profiles between summer and winter BDEW has defined the following day types:

Summer: Monday-Friday, Saturday, Sunday
Midseason: Monday-Friday, Saturday, Sunday
Winter: Monday-Friday, Saturday, Sunday

Once the load profile is chosen and the annual energy demand is available the energy is distributed over one year in 15 minutes time steps with the standard load profile distribution.

## 2.2 Production profile

The production profile is calculated based on meteorological data's from the Meteonorm 7 software. The software calculates the solar radiation on an inclined and oriented surface with the three component model based on measured data's. Additional the corresponding temperature profile is given. Based on these data's the energy yield is calculated based on the principal from Häberlin [2]. The time resolution of the meteorological data's is currently limited to one hour's resolution.

## 2.3 Simulation of on- site consumption

Once the load- and the production- profile is calculated the simulation of the on-site consumption can be easily done with the given equations in chapter 1.2.

# 3. Comparing of load prediction and measured data

## 3.1 Residential building

A typical private residential building from central Switzerland was chosen where a measured load profile of at least one year in a resolution of 15 minutes was available.

| Characteristic | Value |
|---|---|
| Type of load | Residential 2-3 Person household |
| Main energy consumers | washing machine (old device), dish washing machine (new device), no heat pump and hot water boiler (separate energy tariff) |
| Automation | No automation for on- site consumption optimisation |
| Annual energy demand 2013 | 4'794 kWh (measured) |
| Annual energy demand day (07:00 – 22:00) | 2'682 kWh (measured) |
| Annual energy demand night (22:00 – 07:00) | 2'112 kWh (measured) |

Table 2: Characteristics of the residential building

The overlapped load profiles in Figure 3 show that the load profile is extremely inhomogeneous. The load profile is very much depending on the behaviour of the inhabitants especially for residential buildings. In this example the inhabitants consciously shift high loads to night time. At the moment the measurement was made there was no photovoltaic system installed.

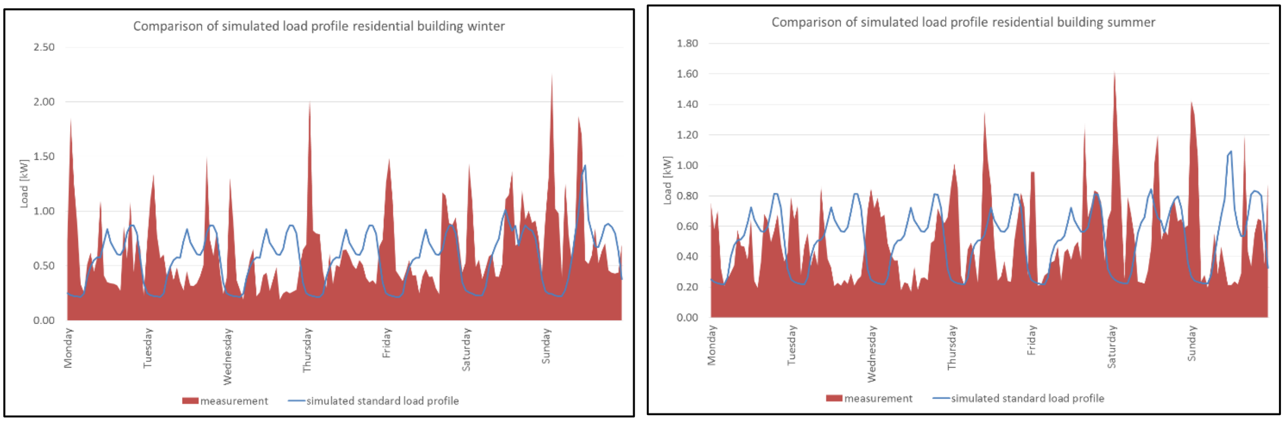



Figure 3: typical weekly winter and summer load profile for residential building sample measured and simulated

The question now is how much are this differences between the measured and simulated load profile effect the simulation of on-site consumption? A measured load profile is normally not available for residential buildings.

After the measurements were made a photovoltaic power plant of 2.05 kWp east and 9.62 kWp west (25° tilled) was installed. This example is used to compare the simulations results with the different load profiles.

| Simulation Result | With measured load profile | With predicted load profile |
|---|---|---|
| self- sufficiency [%] | 192 | 192 |
| self- consumption index [%] | 19 | 26 |
| autarchy [%] | 37 | 50 |

Table 3: comparison of simulation results with measured and predicted load profile

The results are mirroring the impression of the load profiles. The self-consumption index is 7% higher with the predicted than with the measured profile. The difference of the result for autarchy is even 13%. The inhabitant was asked for reasons to explain the load profile. It was found that in case of the measurement the inhabitants were trying to shift load in the night to save money because of the lower energy tariffs. When they installed the photovoltaic power plant, they switched this practise by installing an energy management system which will shift loads to times with much energy production.

## 3.2 School building

With the buildings of the University of Applied Science in Luzern (HSLU) (Technik und Architektur in Horw) a large office building was found where a load profile measurement was available.

| Characteristic | Value |
|---|---|
| Type of load | G3: Continuous industries |
| Main energy consumers | No information available |
| | No automation for on- site consumption optimisation |
| Annual energy demand 2013 | 2'881'373 kWh (measured) |
| Annual energy demand day (07:00 – 22:00) | 1'920'356 kWh (measured) |
| Annual energy demand night (22:00 – 07:00) | 961'016 kWh (measured) |

Table 4: Characteristics of the office / School building

The load profiles shown in Figure 4 are corresponding well except for some peaks at lunch time. The reason for that could be the staff canteen.

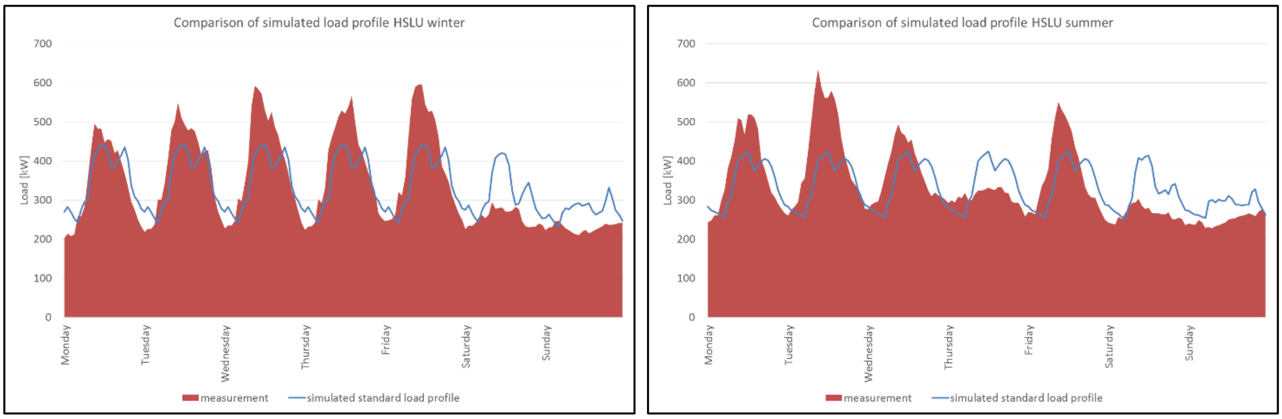



Figure 4: typical weekly winter and summer load profile for office building example measured and simulated

The easiest way to build a large photovoltaic plant on this building would be a standard system on the roof top with a south orientation and 10° tilted mounting system. It would be possible to install around 1.5 MWp. To compare die simulation results with the measured and the predicted load profile this assumed PV-Plant was used.

| Simulation Result | With measured load profile | With predicted load profile |
|---|---|---|
| self- sufficiency [%] | 46 | 46 |
| self- consumption index [%] | 71 | 70 |
| autarchy [%] | 33 | 33 |

Table 5: comparison of simulation results with measured and predicted load profile

With this simulation example the self-consumption index as well as the autarchy is over a time period of one year almost identical. In this case the predicted load profiles give a very good approximation.

If the self- sufficiency would be higher which results in higher production peaks the difference of the results between the two load profiles would get higher.

# 4. Impact of different BIPV orientations

## 4.1 Introduction

One difference between standard rooftop photovoltaics and BIPV for on-site consumption is that the orientation of the photovoltaic cells is not optimized for peak production yield but for load matching. Integration of PV in the east and west façade would yield more energy in the morning and afternoon respectively. To what this distribution of PV in the building envelope influences the self-sufficiency and other criteria is the objective of this chapter. Therefore the same size (Wp) of a photovoltaic system is oriented in different directions and the simulation results compared. Shading form trees or buildings were not considered.

## 4.2 Residential building

For the same building as described above a photovoltaic system of 10kWp is distributed differently resulting in 10 different configurations named **EW 10°** to **F- ESW** as shown in Table 6.

| Direction | Flat Roof 10° | | Roof 25° | Façade 90° | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **name** | **EW 10°** | **South 10°** | **EW 25°** | **F-East** | **F-West** | **F- South** | **F- North** | **F- EW** | **F- NESW** | **F- ESW** |
| East | 5 kWp | | 5 kWp | 10 kWp | | | | 5 kWp | 2.5 kWp | 3.3 kWp |
| West | 5 kWp | | 5 kWp | | 10 kWp | | | 5 kWp | 2.5 kWp | 3.3 kWp |
| South | | 10 kWp | | | | 10 kWp | | | 2.5 kWp | 3.3 kWp |
| North | | | | | | | 10 kWp | | 2.5 kWp | |

Table 6: Simulation configuration for residential building

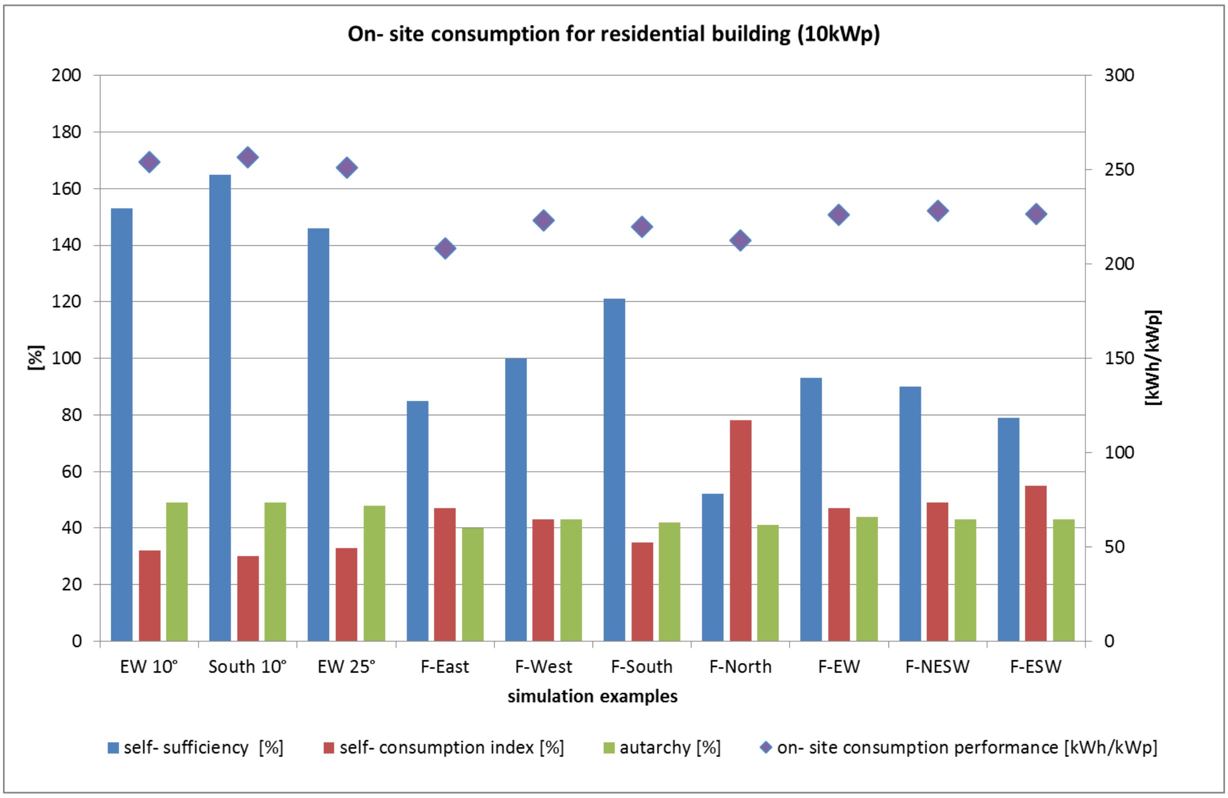



Figure 5: Simulation results for residential building

The simulation results show that the on- site consumption performance (OCP) for building integrated photovoltaic in the façade are between 11 % to 19% lower compared to a south oriented system. A south oriented system produces high peaks at noon, which normally cannot be used directly while the façade system is producing much lower peaks due to the orientation.

The self- sufficiency differs 115% for the different orientations which can be explained by the lower energy production for the façade systems. Conclusion: for on-site consumption the orientation is not that relevant as it is for overall energy production if the self-sufficiency is high (over 100%).

## 4.3 School building

For the same building as described above a photovoltaic generator of 1’500kWp is used for the following simulations.

| Direction | Flat Roof 10° | | Façade 90° | | | |
|---|---|---|---|---|---|---|
| **name** | **EW 10°** | **South 10°** | **F-East** | **F-West** | **F- South** | **F- North** |
| East | 750 kWp | | 1’500 kWp | | | |
| West | 750 kWp | | | 1’500 kWp | | |
| South | | 1’500 kWp | | | 1’500 kWp | |
| North | | | | | | 1’500 kWp |

Table 7: Simulation configuration for school building

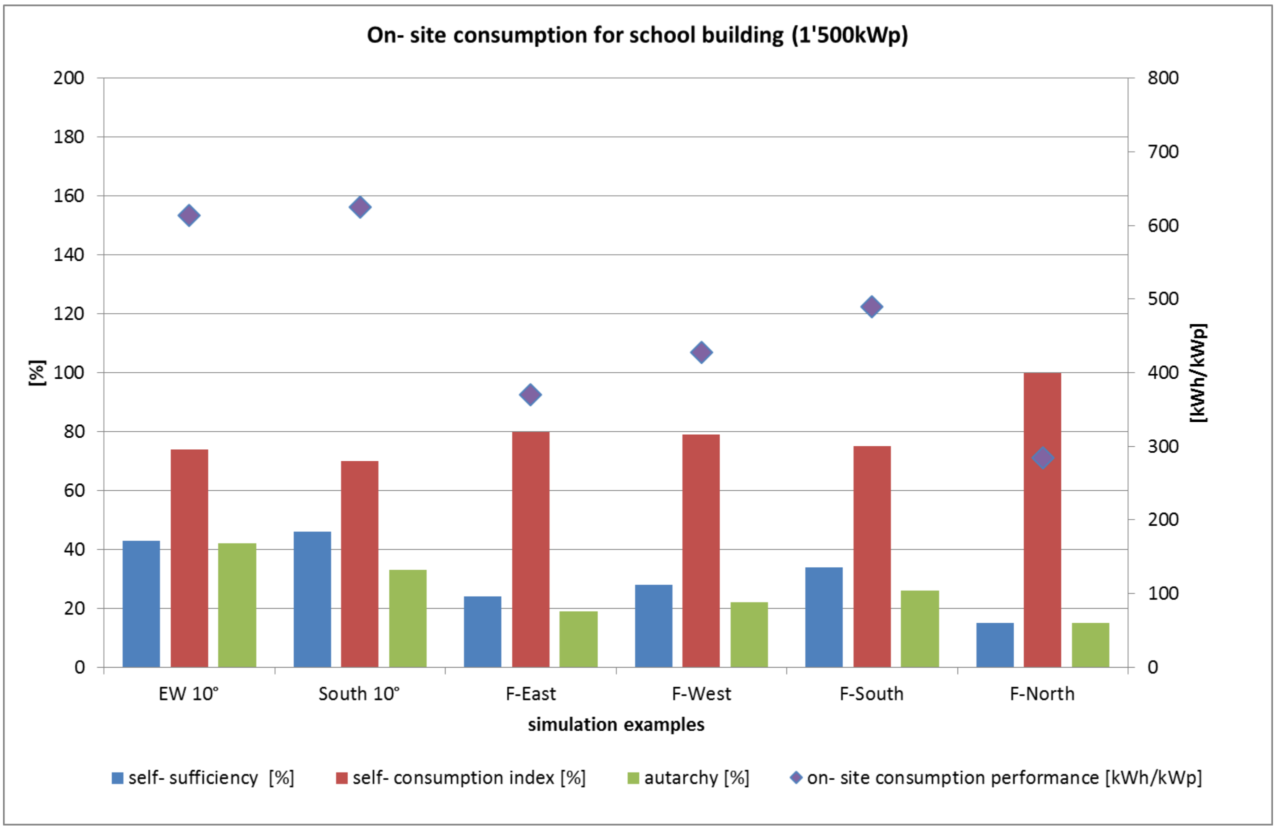



Figure 6: Simulation results for school building

The results show that self-consumption index is highest when al PV is installed on the north façade, however at lowest other performance. If autarchy or on-site consumption performance were the main objectives, than a roof top system with slight tilts towards east and west is best. If only facades were compared, south is better than west, followed by east and north.

## 5. Conclusion and Perspective

On-site energy consumption for buildings with BIPV can be quantified using different terms, from self-sufficiency as a simple percentage of annual contributions to a more complex autarchy approach considering temporal resolution or eventually on-site consumption performance.

The impact of BIPV in the façade on the on- site consumption performance is not as high as on the energy yield of the photovoltaic system. In the business model of on- site energy consumption it is very important to have a high self- consumption index.

The costs for photovoltaic systems dropped during the last 10 to 20 years drastically. The next step of cost reduction is to integrate photovoltaics in building elements. The cost reduction can be achieved by using the characteristics of the photovoltaic front glass as the building envelope and therefor safe costs for alternative materials without energy production. Because photovoltaic needs large surfaces it is important to think about esthetical and architectural integration into the existing building stock as well as in new buildings.

Further, the integration of photovoltaics into the public grid gets more complex with a higher coverage rate. A target would be a seasonal balanced energy production to avoid the need for large energy storage systems and release the local energy grid from high feed in peaks. The production profile of the simulated façade systems (not documented in this report) show improved seasonal and daily distribution of the produced energy.

It is important to have reliable energy profiles for building. The standard load profiles could be extended with special building characteristics (for example: air-conditioning, heating systems, large IT- structure), to improve accuracy of the predicted load profile. The simulations were made with load profiles without considering the load shift potential. By shifting the load in times of production the on- site consumption can be further increased.

Eventually, regulations and business models will determine which criteria to follow and promote. Obviously, façade installed BIPV systems perform well under these criteria, and may thus be a viable alternative when space for rooftop systems is limited.

## 6. Acknowledgements

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