HIGH PENETRATION OF PHOTOVOLTAIC SYSTEMS IN A RESIDENTIAL DISTRICT: AN INNOVATIVE PROJECT FOR THE DECENTRALIZED MANAGEMENT OF DISTRIBUTED ENERGY GENERATION

Davide Rivola*, Matteo Marzoli, Domenico Chianese, Roman Rudel
University of Applied Sciences and Arts of Southern Switzerland (SUPSI), Institute for Applied Sustainability to the Built Environment (ISAAC), CH-6952 Canobbio, Switzerland
*Phone: (+)41 58 666 63 56; Fax: (+)41 58 666 63 49
www.supsi.isaac.ch E-mail: davide.rivola@supsi.ch

ABSTRACT: The high penetration of PV systems in a residential district reduces the use of fossil fuels, emission of CO_2 and pollutants and energy losses, but requires a fine-tuned management of the grid. Within the Swiss2Grid (S2G) pilot project, 20 private households in the same district have been equipped with smart PV energy production units. The installations have been provided with high quality monitoring systems, in time match with monitoring devices installed in the distribution grid and the LV transformer. The collected data are used to support the development of an algorithm for the decentralized management of households loads. The results of the preliminary measurements campaign are presented before applying the algorithm.

Keywords: grid integration, self-consumption, monitoring, demand-side

1 INTRODUCTION

The high penetration of PV systems in a residential district is a great chance for reducing the consumption of fossil fuels and the emission of CO_2 and pollutants, but also it is a chance for the reduction of the energy losses and the load profile on the electric low voltage distribution grid. This requires a fine-tuned management of the grid performed through a precise prediction of the loads, high resolution and synchronized measurements at house level and at low voltage (LV) transformer level, and an efficient algorithm of management.

Within the Swiss2Grid (S2G) project, 20 households in southern Switzerland (Mendrisio) were equipped with accurate monitoring devices. Relevant loads (e.g. heat pumps and water heaters) have been retrofitted for smart control. New devices (e.g. battery-to-grid systems and smart electric car chargers) have also been introduced. The data are complemented with time-synchronized measurements at the low voltage (LV) transformer.

A high quality grid monitoring system has been installed in order to observe local effects of PV generation and to support the development of an algorithm for the decentralized management of the household loads.

In Section 2 we present the pilot and demonstration components of the project and the preliminary measurement campaign. Section 3 analyzes the self-consumption rate of the PV systems. Section 4 compares the difference on voltage and power between high and low irradiance days. In the last section we recapitulate our findings.

2 APPROACH

The overall goal of the project is to investigate in a pilot project the technical feasibility of decentralized electric energy production, storage and consumption by combining available and new technologies in an intelligent and system.

The basic idea of the project is to optimize the load management on the local grid by an algorithm based on decentralized decision making with limited information in single nodes (appliances) and to understand its overall impact on the grid performance. The present project wants to show to which extend the need of two-way communication systems capable to manage the smart grids can be reduced and the problems related to the elaboration of huge quantities of information overcome. This represents an innovative approach of the grid management based on intelligent devices with self–optimization capabilities at the level of each node. The mathematical model of this approach is described in [1].

2.1 The households selection

The 20 households involved in the projects were identified from 134 candidates, forming several clusters based on LV transformer connection, availability of electric vehicles and desired installed PV power. The candidates are represented in Figure 1. Each household is depicted by a filled circle. The district electric distributor, Aziende Industriali Mendrisio (AIM), identified the connected LV transformers, shown with filled triangles. Color coding enables to identify the transformers clusters.

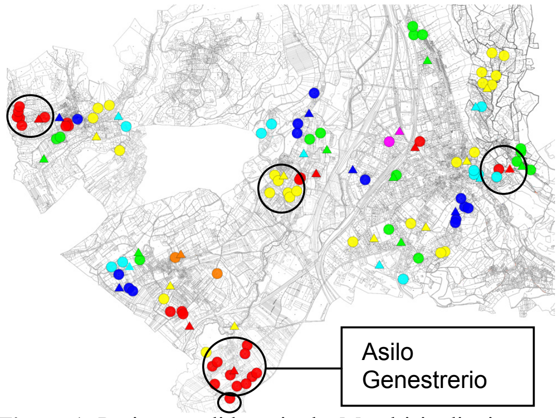

Figure 1: Project candidates in the Mendrisio districts. Selected clusters are identified by the black circles.

The most interesting selected group is the "Asilo Genestrerio" neighborhood, whereas the 10 households represent more than 10% of the total customers connected to this particular LV transformer.

During the recruiting process the house owners expressed in general very good attitude to participate actively in the demonstration phase. They also incremented the granted PV power by buying their own PV modules, indicating high sensitivity to energy and environmental issues: total installed generating power is 88.13 kWp instead of planned 30 kWp (the quantity offered by the project). This size is not negligible for the Swiss context, a nation currently characterized with a low diffusion of decentralized photovoltaic generation (less than 1% [2]).

The on-site survey identified suitable locations for the installation of 4 battery-to-grid systems and the control of 10 heat pumps and electric heaters. It was also possible to identify three candidates who were willing to buy an electric car.

2.2 The Household Appliance Controller

After the PV system set-up, the houses were outfitted with the monitoring equipment. The device, called household appliance controller (HAC), is a custom electronic system developed by the Swiss2Grid project. The HAC measures with high precision the relevant grid values, as voltage, current, frequency, active and reactive power.

The unit is housed in a DIN mounting box and it can transmit the measured data over a powerline bus (Echelon), enabling an easy installation in the households without major modifications of the cabling. The communication protocol is also used for time-stamping the acquired data via the Network Time Protocol (NTP).

In total 160 devices were produced in order to monitor the grid connection points and the relevant appliances of the households. Figure 2 shows an example of HAC installations.

Figure 2: Example of household appliance controller installations. The devices are acquiring data from the PV systems and the house grid connection points.

2.3 The first measurement campaign

The topology of the “Asilo Genestrerio” LV network is detailed in Figure 3. The filled triangles represent the participating households, equipped with the HACs. Additionally, two grid monitoring devices were installed at the green dots location, measuring the currents leaving the transformer towards the houses on two different radial branches. The same type of equipment is installed at the houses represented with red triangles.

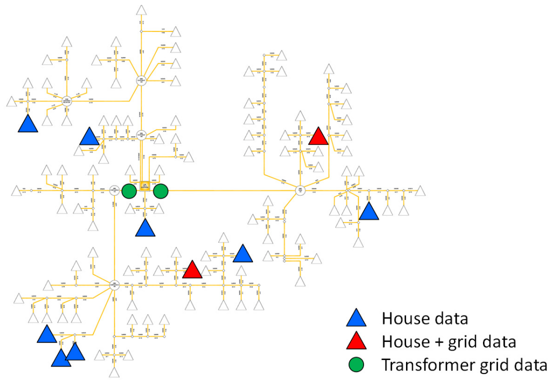

Figure 3: Detailed topology of “Asilo Genestrerio” low voltage distribution grid.

The measurements are time-stamped via a GPS signal. The time-accuracy of the acquired data enables to complement the HAC measurements. The quality and reliability of the system has been tested and verified during the rollout phase. Moreover, an automated daily data quality verification has been implemented, alerting the researchers in case of missing or incorrect data allowing a reliable and effective support of the devices operation.

The first measuring campaign has been performed before applying the algorithm in order to assess the initial conditions of the pilot installations. The data allow to perform several set of experiments for the algorithm development (see [3] for details).

In the following sections we evaluate the PV effects on the households and the low voltage distribution grid.

3 PV SELF-CONSUMPTION RATE

The PV self-consumption rate is defined by the fraction of the generated power consumed by the local loads. Households with a similar size of PV installed power are selected from the “Asilo Genestrerio”. The main characteristics of the households are shown in Table I .The period from February to August 2013 is considered in order to include seasonal effect.

Table I: Main characteristics of the selected households.

Households	HH06	HH09	HH01	HH11
PV power [kWp]	5.0	4.5	4.5	4.5
PV energy [kWh]	3650	3157	2422	3087
Heating type	heat pump	heat pump	gas	gas
No. persons	4	2	4	1

Figure 4 represents the PV self-consumption calculated for the whole period. The values range from 22% to 42% and are in line with the results of other evaluations of self-consumption [4].

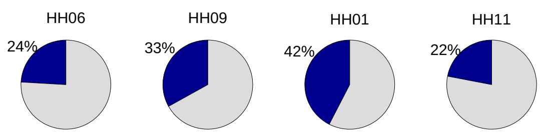

Figure 4: Total PV self-consumption of the selected houses in the observed period (February-August 2013).

Although the photovoltaic systems are installed in the same area, their energy production is variable. In particular, the HH01 house presents a very low energy yield, due to a combination of a low inclination of PV modules and a very high local shadowing effect from the neighbor's houses and trees.

The rate is also influenced by socio-economic factors. In example, the HH11 is inhabited by a single person and the house shows the lowest rate of self-consumption.

The load and generation profiles are not usually constant during the year, it is therefore important to analyze the self-consumption with finer details. Figure 5 illustrates the monthly self-consumption rate for the same period and set of houses.

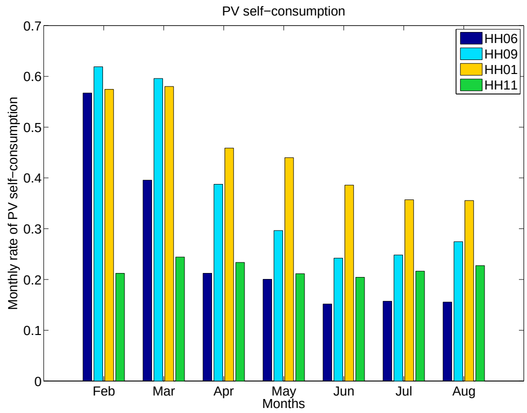

Figure 5: Monthly PV self-consumption rate of the selected households (February-August 2013).

A seasonal variation on PV self-consumption is noticeable. A cause of that is the fluctuation of the photovoltaic energy production during the year. The other and most important cause is the higher consumption during winter and early spring due to the usage of electric heating systems. This is supported by the fact that, the houses which are characterized by higher variations (HH06 and HH09), are equipped with heat pumps.

The electrical heating systems have already a considerable effect on the self-consumption. However there is still room for further improvement of these values by applying a smart control algorithm.

The seasonal variation also highlights the necessity to introduce new elements of energy storage such as electric vehicle smart chargers and battery-to-grid systems in order to increase the self-consumption during the warmer part of the year. Another interesting measure could be to disable the ripple control system, currently used by the distribution network operator to activate the water heaters during the night. This measure would give additional freedom to a smart algorithm to control these loads.

4 COMPARISON BETWEEN HIGH AND LOW IRRADIANCE DAYS

To analyze the impact of the PV systems on the households and the grid, the previously selected houses are used. A shorter period from May to August 2013 is chosen in order to exclude the seasonal variations previously discussed.

By using a combination of Perez's clearness index, sky ratio and clearness index, calculated from local meteorological data, the days in the observed period are clustered by the following categories of irradiance: very clear, clear, cloudy and overcast. The table II shows the percentage of days for each category.

Table II: Clustering of observed days by irradiance type

	Percentage of days
Very clear	12.7 %
Clear	23.3 %
Cloudy	54.2 %
Overcast	9.8 %

In the comparison, the cloudy days are excluded and the very clear and clear days are grouped together in order to strongly differentiate days with high PV generation from days with low PV generation.

4.1 Voltage values distribution at households grid connection

The impact of PV generation on voltage profiles in LV distribution network is a growing research topic. The presence of a generation unit produces a rise of the voltage profile [5] [6] [8]. High penetration levels of PV can also cause voltage instabilities [7]. Most of these research studies have been performed in simulated environment. It is interesting to analyze the data acquired from the installed equipment to see if it is possible to detect the impact of PV.

The relative cumulative frequency of the measured voltages has been calculated. Figure 6 shows the results for the HH06 house. The impact of the PV generation is visible. The high irradiance days are characterized by higher voltages.

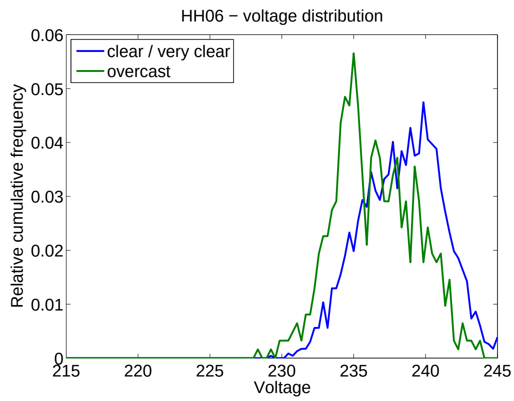

Figure 6: Voltage distribution at HH06 between clear/very clear and overcast days. Selected period is May-August 2013. Total LV line length is 575m.

Figure 7 represents the results for the HH01 house. This house is connected to the same radial branch of the transformer and by a similar length of LV lines. The total installed PV power in the branch is 20.0 kWp. In this case the effect of the photovoltaic is noticeable and similar to the HH06 house.

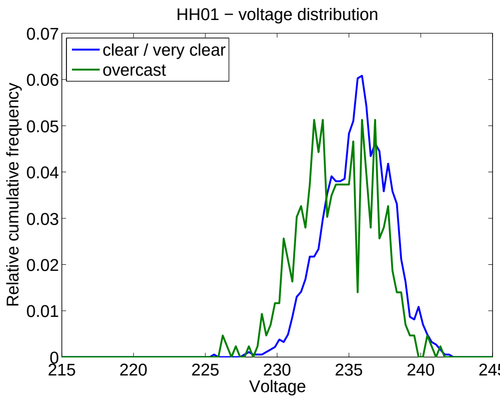

Figure 7: Voltage distribution at HH01 between clear/very clear and overcast days. Selected period is May-August 2013. Total LV line length is 624m.

The HH09 household is located in another radial branch of the "Asilo Genestrerio" transformer. The total installed PV power is significantly less (8.0 kWp). The total length of the low voltage line is 267m, less than an half of the previously discussed households. As shown in Figure 8, the voltages are higher and less distributed, as expected. An effect of the PV generation in this branch is not noticeable due to shorter LV lines and less installed generation power.

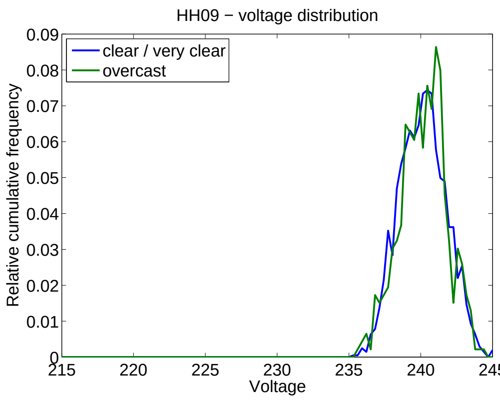

Figure 8: Voltage distribution at HH09 between clear/very clear and overcast days. Selected period is May-August 2013. Total LV line length is 267m.

A similar behaviour is shown for the HH11 house in Figure 9. This household also has a shorter LV line connection and it is served by another branch of the transformer with the lowest total installed PV generation (6.5 kWp).

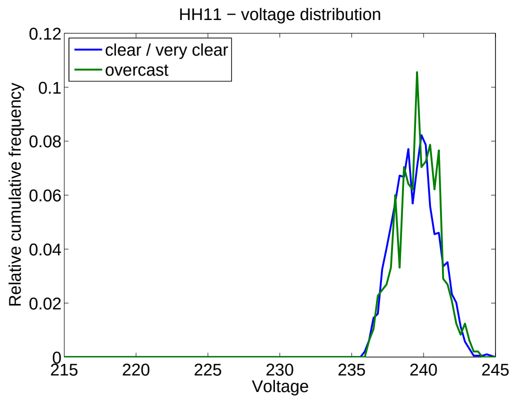

Figure 9: Voltage distribution at HH11 between clear/very clear and overcast days. Selected period is May-August 2013. Total LV line length is 279m.

The selected households indicate a strong distribution network with values generally over the rated voltage of the grid (230 V). This limit the impact of the PV systems, which is visible on longer LV lines. The distribution of voltages varies following the LV line length. Shorter lines show higher and less distributed values.

4.2 Power values distribution at the transformer radial branch

The data measured at the LV transformer output branch "campagnola" (serving HH01 and HH06) are evaluated for the May-August period. This branch is connected to higher number of PV installation for a total of 20.0 kWp PV power.

Also in this case, the period is selected with the intention to exclude the seasonal variation due to the electrical heating appliances. The relative cumulative frequency of the active power values is shown in Figure 10. The transformer power is reduced by around 10 kW on high irradiance days.

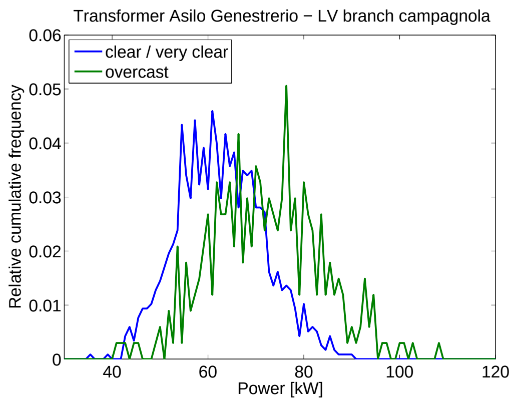

Figure 10: Active power distribution at the output branch "campagnola" of the LV transformer between clear/very clear and overcast days. Selected period is May-August 2013.

The effect of the PV generator connected to this radial branch is noticeable. The size of the active power shift (around 10kW) is in line with the generation power (20 kWp).

4 CONCLUSIONS

The Swiss2Grid pilot and demonstration project has been introduced. A high quality grid monitoring system has been installed in order to support the development of an innovative decentralized approach based on intelligent devices with self–optimization capabilities at the level of each node.

The currently unmanaged loads operation is not optimal. The generation profile of the house is not synchronized with the load profile, showing a variable self-consumption depending on technical parameters, user's behaviour and seasonal variations.

This represents promising opportunities for the algorithm operation, optimizing the household interaction to the distribution grid by load shifting. The data show a good chance of reducing the power flow on the grid with the development of a high level algorithm for the existing loads management, and the need of introduction of new appliances (e.g. electric vehicle charges and battery-to-grid systems) to compensate the seasonal variations.

An impact of photovoltaic generation on the local voltages has been shown in selected cases. The voltage level at the household plug is a useful input signal for a fully decentralized smart algorithm.

Future work will focus on evaluating the impact of the introduction of the smart algorithm on the low voltage distribution network in Mendrisio. This evaluation will be complemented by simulations with higher penetration of PV, smart loads and storage systems.

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