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INTEGRIDS

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Electric and thermal grids integration with energy flexible building

Titolo del progetto:

Studio dell'integrazione di reti elettriche e termiche con la flessibilità energetica degli edifici

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Executive summary

In the recent years the high renewable sources penetration and the increasing of the electrical loads, mainly due to the electrification of the mobility and the heating sectors, is consistently changing the energy systems management. The electrical and thermal grids, born to work separately in the past, are now becoming integrated and able to interact effectively in order to properly fulfil the end user needs. It is important to highlight that, due to the climate/ambient objectives, the electrical and thermal grids should operate together to maximally exploit the green energy provided for example by photovoltaics installations. This purpose can be achieved using dedicated devices to store the PV production surplus (such as batteries) and/or to develop intelligent logics able to shift and shave the load or to modulate the power. These concepts and their logics, usually very sophisticated are sometimes well modelled and simulated in different suitable software environments as demonstrated in the literature. Due to the complexity of the involved system and the possible scenarios their experimental tests are not so common. Within this context born the idea of the INTEGRIDS project.

The project has been funded by the European Regional Development Fund for the Province of Bolzano with the aim to develop modelling and experimental environments to study and test the integration of electrical and thermal grids with building flexibility at district level. In this direction the project has developed modelling environment to test energy grid at national and regional level, forecasting algorithm for production and demands, power flow model for electric grids and defined and simulated the flexible building concept. Moreover, one of the main objectives of INTEGIRDS has been to design and build additional infrastructure to the already existing outdoor laboratories of the Institute for Renewable Energy in order to emulate a virtual microgrid. Indeed, thanks to the project, three laboratories dedicated to PV integration, district heating demonstration and flexible building emulation have been connected through a digital infrastructure to be able to exchange data in real-time during run experiments. In addition, a central database has been implemented to use the store data for real-time or offline computation. The technical details of the infrastructure have been described in the dedicated reports (i.e. D5.1 and D5.2) in this last report the correct operability of the “INTEGRIDS” laboratory has been presented.

Nevertheless the results reported in this document are interesting not only to show the function of the lab, but also the validity of the concept in terms of renewable energy maximization, it is relevant to say that the powerful of the deployed infrastructure is more than an ending point a starting point. Indeed, due to the recent European Renewable Energy Directive 2018/2001 where the Renewable Energy Communities (REC) will be the future paradigm for the local energy exchanges, the work performed in INTEGRIDS will be and should be used to continue the theoretical and applied research in this build with the possibility to the test the REC logics in a controlled but in the meantime complete energy systems.

1 Introduction

The INTEGRIDS project has been developed under the grant of the European Regional Development Fund for the Province of Bolzano, with the aim to develop modelling and experimental environments to study and test the integration of electrical and thermal grids with building flexibility at district level. While the modelling and conceptual parts related to the energy grids and flexible buildings are well described in the reports related to the activities performed in work packages 3 and 4, the design, implementation and conceptualization and validation of the laboratory infrastructure have been part of work package 5 of which this report is part.

In particular, starting from the three single laboratories (i.e. *PV Integration Lab*, *Energy Exchange Lab*, and *Multi-Lab)* present in the outdoor area of the Institute for Renewable Energy of Eurach Research, a robust communication infrastructure, with a central control server and a centralized database, have been implemented (as described in detail in D5.1 and D5.2). This allows to monitor and control the three laboratories that now are not only able to work singularly but also to interact in real-time as a virtual micro-grid.

Thanks to the infrastructure developed during the project INTEGRIDS, it will be possible to develop several kinds of test which involve one or more laboratories in real or not real-time. Indeed, the presence of the database which stores all the experiments allow us to use experiment results not only for post-processing computation, but also for different simulations or for model validation. This type of experiments will be in the following indicated as off-line tests. On the other hand, the real-time exchange of the data between the laboratories and the central processing unit (CPU) are able also to operates for real-time tests. The CPU implement the energy management control and is able to send the operational signal to the different laboratories in order to achieve the common objectives (e.g. maximize use of renewable). The single laboratories can accept or not the requests depending on its status. Everything will be reported and analysed by the researchers.

The rest of the document is dedicated to the description of the design and results of two experiments: one offline and one online, according to the definition provided in D5.2. These tests have been done to demonstrate first of all the properly communication and data exchange between the involved laboratories and then through a simple control algorithm to explore the powerful of the integrated laboratories to validate future system with maximally exploitation of renewable energies.

2 Offline experiments

2.1 Objectives of the test

The goal of the offline test is to show how the digital infrastructure developed within the INTEGRIDS project could be used in offline mode and to show an example of application. In the offline mode there is not a real-time communication between the test facilities involved, but experimental data collected from the different laboratories are used at the end of the specific tests.

The objective of this example test is to determine the optimal capacity of a photovoltaic system that could be properly coupled with the domestic hot water (DHW) production and space heating (SH) system of a residential building.

2.2 System

The system used in this analysis is a virtual system composed by a 1.5 kWp photovoltaic system installed at the PV integration lab and part of the prosumer substation of the Energy Exchange lab described in D5.2 (4.1.1 The Energy Exchange Lab description) of the INTEGRIDS project. It follows a list of the main components of the plant:

- a real water-to-water heat pump
- a virtual domestic hot water storage tank emulated with TRNSYS (D5.2, 4.1.2)
- a virtual storage tank for the space heating system emulated with TRNSYS (D5.2, 4.1.2)
- real 1.5 kWp photovoltaic system
- a virtual building located in Bolzano

The heat pump provides the heat required to maintain the temperature inside the virtual domestic hot water and space heating storages at the setpoint temperatures (50°C for DHW and 38°C for SH). The storages are virtually discharged by a simulated DHW and SH thermal demand obtained from the virtual building model, while in the real plant the heat is rejected thanks to the heat rejected circuit. During the experiment, the electric consumptions of the heat pump is measured and saved on the INTEGRIDS database.

At the same time, power production data of the grid-connected photovoltaic system are collected and saved on the same database. The PV system used to collect production data is referred as the reference system in this document.

2.3 Data

At the end of the experiment (four days of operation of the heating system), electric consumption of the heat pump and PV production data are downloaded through the INTEGRIDS API described in D5.2. The API allows to download in a Python environment the data saved on the INTEGRIDS database for data processing and analysis. Measurements are then analyzed to detect missing data (and eventually fill them) and to align the time index of consumption and production. Finally, data are resampled with a 15 min frequency to reduce the computational time required for the optimization without compromising the accuracy of results. The resampled data are equal to the average value of the measurements collected in each time-interval. Finally, production data are rescaled to obtain the power production per unit nominal power (1 kWp).

2.4 Optimization

The objective of the offline test is to find the optimal size of the PV system coupled with the heating system under analysis. Thus, the parameter of the optimization is a scaling factor for the production power of a 1kWp system (e.g. if the scaling factor is 10, the optimal PV system nominal power is 10kWp). The power of the 1 kWp system is calculated as the ratio between the measured power and the nominal capacity of the reference system (1.5kWp). Even if in this specific case the optimal solution could be found with simpler algorithms, it was chosen to implement a multi-objective genetic algorithm to facilitate the possible future development of the optimization problem.

Two relevant KPIs are defined as fitness function of the optimization problem: self-sufficiency (SS) and self-consumption (SC). The two KPIs describes well the behavior of the PV system coupled with a demand profile and are commonly used to evaluate PV systems. Self-sufficiency is the ratio between the self-consumed energy and the total consumed energy, and it describes the percentage of the electric demand covered by the PV system. Self-consumption is the ratio between the self-consumed energy and the total energy produced by the PV system, thus the percentage of produced energy that is self-consumed.

$$SS = \frac{\sum self-consumption}{\sum consumption} \qquad SC = \frac{\sum self-consumption}{\sum production}$$

SC and SS are used as objective of the two-objective optimization algorithm: the goal is to maximize the self-consumption and the self-sufficiency of the PV system. Figure 2 summarizes the optimization process.

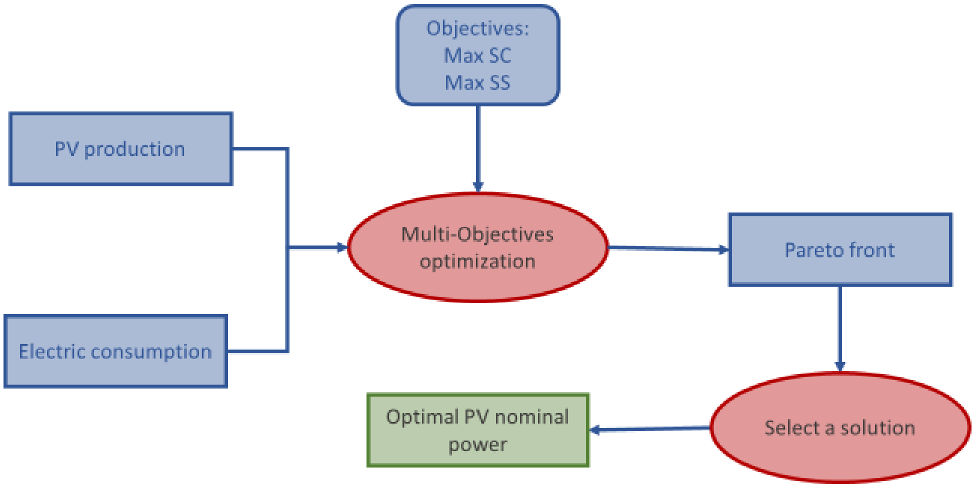

Figure 1 - PV sizing algorithm

2.5 Results

Since the optimization is based on a multi-objective optimization algorithm, the final solution is a set of optimal non-dominated solutions identified by the Pareto front represented in Figure 2. As expected, since the two indexes are conflicting objectives, the SS index increases at the decreasing of SC. Referring to the right side of Figure 2, for small plants with nominal power P_n lower than 5kWp, SS is close to 0% meaning that the PV plant can cover only a small part of the electric consumption. On the contrary, SC is high (approximatively 100%), meaning that the energy produced is almost self-consumed. These values are typical of undersized systems. The opposite situation can be found on the left side of the Pareto front, where the PV plant covers a higher percentage of the energy consumed; at the same time, more energy is not used and is feed into the grid (SC close to 0%).

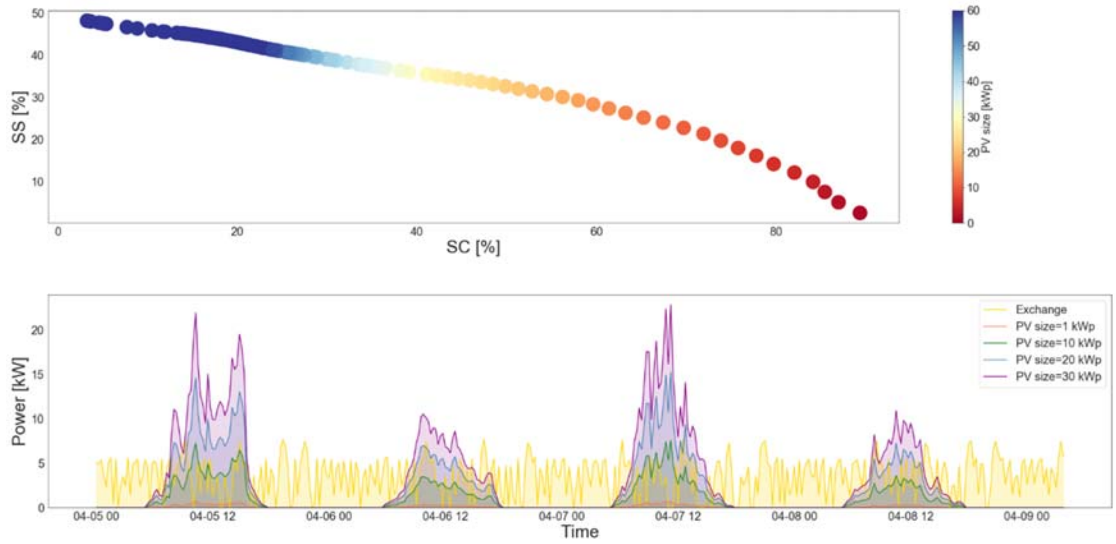

Figure 2 – PV production at different plant nominal power

To identify a unique scaling factor for the PV system, the set of optimal solution is filtered according with the following thresholds: SC>65% and SS>20%. Thresholds where set to avoid oversized and undersized systems. The final solution is identified as the one corresponding to the minimum scaling factor obtainable multiplying the reference nominal power (1.5 kWp) by an integer number. The following summarizes the final solution. In particular in Table I the identified value of PV peak power with the corresponding SC and SS are reported. While Figure 3 – PV production and heat pump consumption profilesFigure 3 shows the behavior over the time the synthetic PV profile in green and the heat pump in yellow respectively.

Table 1 - Result size of PV to be installed with the correspondent self-consumption and self-sufficiency

Size [kWp]	SC [%]	SS [%]
12	67.5	24

2.6 Conclusions

The offline test successfully demonstrated the interconnection between the photovoltaic and the Exchange laboratories showing one of the potential uses of the offline mode. The interconnection between the thermal and electric grid opens different research topics that could be investigated thanks to the digital infrastructure created within the INTEGRIDS project. Moreover, the offline test set the basis for the development of the online test, a higher-level application where the electric and thermal systems exchange data and information in real time.

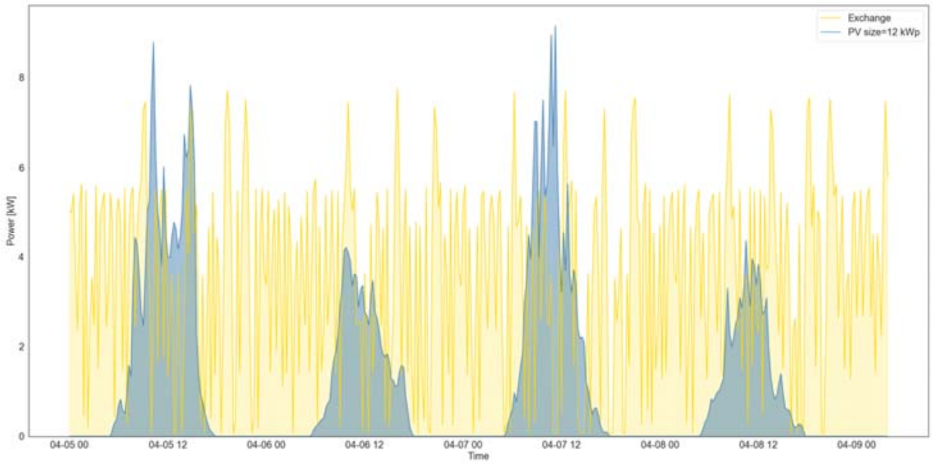

Figure 3 – PV production and heat pump consumption profiles

3 Online experiments

The online integrate experiment done within the INTEGRIDS digital infrastructure involves the Energy Exchange and the PV integration lab and it is described below.

3.1 Objectives of the test

The objective of the test is to verify the communication between the PV integration Lab and the Energy Exchange Lab through the INTEGRIDS digital infrastructure. In details, a control logic has been implemented into the INTEGRIDS central control server with the aim of partially controlling the HP operation installed into the Energy Exchange Lab based on the PV production of PV panels installed into the PV integration Lab. Moreover, all the data of interest for the test are saved into the INTEGRIDS database. Finally, base evaluations have been done to maximize the use of the PV production to cover the HP consumption.

3.2 Description of the test

The online test done provides for the operation of the HP of the Energy Exchange lab in heating mode coupled with two virtual tanks, one for space heating (SH) and one for domestic hot water (DHW), as described in D5.2. The tanks are used to satisfy the space heating and domestic hot water demand profiles of a single-family house (SFH). The profiles used are the results of simulations. The control strategy of the HP is mainly based on the rule-based control, as described in D5.2. In details, it consists of two mutually exclusive hysteresis that control the temperature at the top of DHW TES and at the top of the space heating TES in winter time (thermostatic control in Figure 4). The control of the DHW TES has priority over the control of the buffer TES.

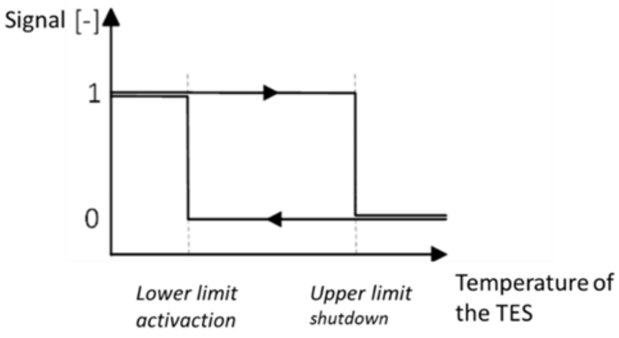

Figure 4: Thermostatic control for heating a TES.

The limit for the activation and shutdown of the hysteresis A and B (respectively DHW and SH test) are listed in Table 2.

Table 2: Parameters of the thermostatic control hysteresis.

Hysteresis name	Acquisition signal	Lower limit activation	Upper limit shutdown
Signal A	Top temperature of the DHW TES (TM1) to assess if the energy content is sufficiently high to cover the DHW request.	45 °C	50 °C
Signal B	Top temperature of the buffer TES (TM3)	32°C	38°C
Signal C	Top temperature of the DHW TES (TM1) for extra charge.	50 °C	55 °C

To consider the PV production, the rule-based control is modified by including an extra charge of the DHW tank by increasing the upper limit of the top temperature to 55°C. A further hysteresis has been implemented into the Exchange control software to manage the extra charge. It is identified as Signal C in Table 2. The extra charge function has been implemented into the INTEGRIDS central control server and it sends an extra charge request to the Energy Exchange control software, as a binary signal, if the following conditions are verified:

- the PV production of the PV panels installed into the PV integration lab, multiplied by a scaling factor equal to 8 (to obtain the production of an equivalent 12 kWp system, see 2.5) is above 7 kW (average electric power consumed by the heat-pump in DHW mode).
- the top temperature of the DHW storage is below 55°C.

The extra charge request sent to the Energy Exchange control software can be accepted or not. It is rejected mainly if the top temperature of the DHW TES is between 45°C and 50°C or between 50°C and 55°C and the hysteresis signals showed in Figure 4 is 0. A feedback signals, as a binary signal, is sent to the INTEGRIDS central control to communicate if the extra charge has been accepted or not.

3.3 Results and comments

During the test, data are collected and saved into the INTEGRIDS database where they can be consulted in real time or at the end of the test. Data analysis confirms that the INTEGRIDS infrastructure allows real-time communication between the laboratories involved. During the online test all the measurements were collected and saved properly, with the only exception of the interval between 00:28:39 e le 00:29:15 of the 4th day of the test, where the signal related to the temperature at the top of DHW TES was interrupted. In this case, data are linearly interpolated to fill the gaps. As shown in Figure 5, the extra charge request was properly elaborated by the INTEGRIDS central control, always respecting the thresholds both in terms of power produced by the PV plant and the top temperature of the DHW storage. During the four days of operation, the extra charge request was accepted 23.2% of the total, in all other cases the Energy Exchange software rejected the request due to the hysteresis that regulates the temperature of the storage as explained in Section 3.2. Approximately, in good weather days the extra charge of the DHW storage was activated twice per day.

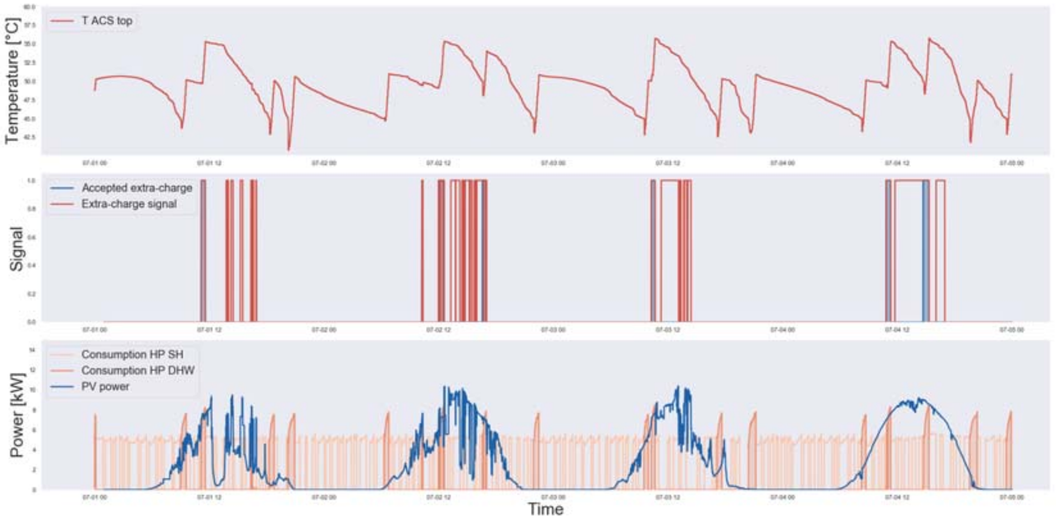

Figure 5: Online test plots

Focusing on the last day of the test (best weather conditions), two extra-charges were activated:

- Extra-charge 1:
  Start: 2020-07-04 10:49:46
  End: 2020-07-04 11:18:00
  Duration: 28.2 min
- Extra-charge 2:
  Start: 2020-07-04 14:42:20
  End: 2020-07-04 15:18:22
  Duration: 36.0 min

Moreover, in Figure 6 it is possible to notice a delay of about ten minutes between the initial request of extra charge and the increase in temperature. The delay is mainly caused by the starting time of the heat pump and the time required by the heat pump to supply heat at a temperature value higher than the one measured by the top temperature sensor.

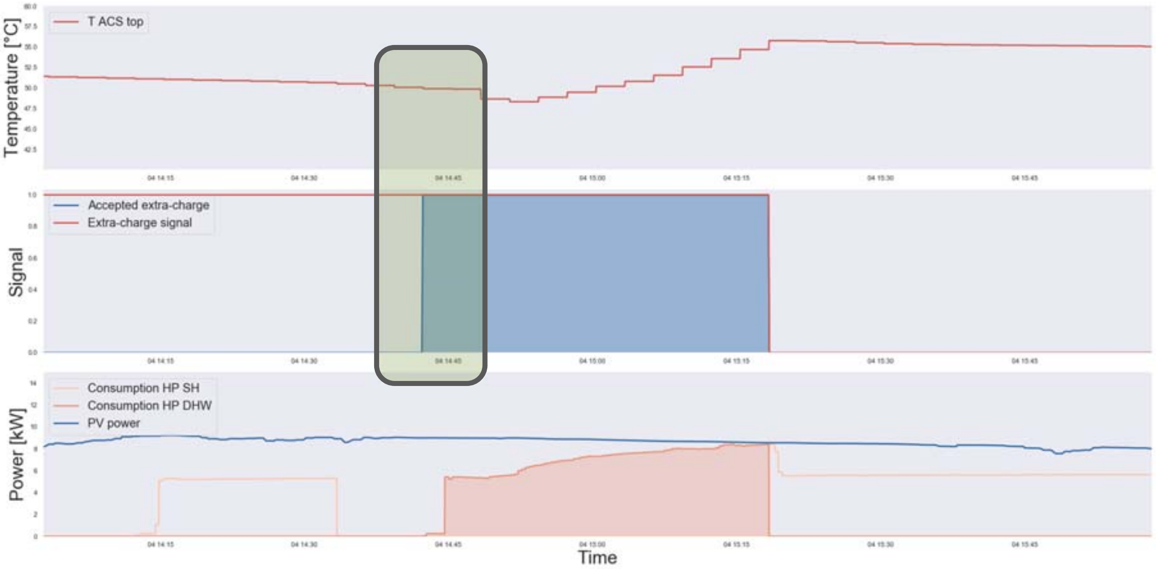

Figure 6: Delay between the request and the temperature increase

In the following tables, the results are compared with the ones of a similar test performed in April 2019 without any communication or interactive logic between the PV integration lab and the Exchange Energy lab. The two tests have the same configuration and thermal demands but have different boundary conditions caused by the different season of the test (the most important difference refers to the external air temperature). The PV production is assumed to be the same for the two tests; for this purpose, the production collected during the online test was selected. The objective of the comparison is to verify the impact of the online control logic assuming the same PV production. The following tables report the values of the self-consumption (SS), self-sufficiency (SC), total energy produced by the PV integration lab, electric energy consumed by the heat pump, the energy self-consumed and the one purchased from the grid. The indicators are evaluated for three different cases: domestic hot water (DHW) demand (Table 3), space heating (SH) demand (Table 4) and total demand (Table 5).

Table 3 -Energy performance indices result comparison between the case with and without extra-charge to cover domestic hot water (DHW) demands

DHW		
	Extra-charge	**No extra-charge**
SC	11.42%	9.9%
SS	44.4%	41.3%
Energy produced	239.6 kWh	239.6 kWh
Energy consumed	61.7 kWh	57.5
Energy self-consumed	27.4 kWh	23.8
Energy from the grid	34.3	33.7

Table 4 - Energy performance indices result comparison between the case with and without extra-charge to cover space heating (SH) demands

SH		
	Extra-charge	**No extra-charge**
SC	39.6%	38.2%
SS	37.0%	36.6%
Energy produced	239.6 kWh	239.6 kWh
Energy consumed	255.9 kWh	250.3
Energy self-consumed	94.8 kWh	91.6
Energy from the grid	161.1	158.7

Table 5 - Energy performance indices result comparison between the case with and without extra-charge to cover space heating (SH) and domestic hot water (DHW) demands

SH+DHW		
	Extra-charge	**No extra-charge**
SC	51.9%	49.2%
SS	38.6%	37.7%
Energy produced	239.6 kWh	239.6 kWh
Energy consumed	322.2 kWh	312.6 kWh
Energy self-consumed	124.4 kWh	117.8 kWh
Energy from the grid	197.8	194.8

The comparison between the two test shows how the online control logic causes a slight increase of the SC and SS indexes due to the DHW extra-charge during the hours of higher production of the PV plant. This is also confirmed by the increase of energy self-consumed. On the other hand, the simplicity of the control logic cannot counter-balance the worst performances of the system which causes an increasing of the energy purchased from the grid. In fact, as it results from the tables, energy consumed by the system for SH and DHW TES charge increases. It could be due to different factors:

- the extra charge increases the temperature of the DHW TES. This causes also higher thermal losses respect to the case without extra charge if the energy extra charged is not used instantaneously.
- the HP has worst performance during the extra charge due to higher temperature difference between condenser and evaporator respect to the case without extra charge. During the test the inlet temperature at the evaporator side is kept to 15°C and the temperature at the condenser changes by causing according to the operation mode. The performances of the HP decrease as the temperature at the condenser increases.
- The return temperature to the HP in SH mode is controlled by a 3-way valve according to the simulated value. This temperature influences the HP performance, as described into the previous point. It is usually in the range 25°C-35°C but can assume values lower than 25°C in some conditions with higher HP performance. During the test without extra

charge it was possible to have all the simulated temperature, while in case of extra charge only values higher than 28°C could be emulated, to higher ambient temperature. This could influence the energy consumed by the HP by increasing it for the same heat supplied

Moreover, considering the small difference between the results of the two tests, measurements accuracy (around 1% for the signals considered) could have a relevant impact on values used for the comparison.

4 Conclusions

The present document reports the results of two experiments performed using the digital infrastructure built during the INTEGRIDS project. The first test has been developed offline. Using the heat pump electricity demand stored in the INTEGRIDS database during an experiment of the Exchange laboratory, the data are used in an optimization algorithm to properly size the PV system in order to achieve targets self-consumption and self-production. The second test has been done online using the PV integration and the Exchange laboratories. The first goal of the experiment has been first of all to test the correct behavior of the communication infrastructure for both monitoring and control purposes. The implemented control has the aim to use the PV generation for thermal storage extra-charge in order to increase the use of renewable for heating demand. This objective has been achieved even as it is possible to note from the table of results the difference between extra and normal charge in the considered parameter is very small. This is due to the simple control used. In the future, the digital infrastructure built during the Integrids project will be extended and tested with different and advanced control which should take into consideration virtual electrical storage, generation or load forecasting, price variations, and many other scenarios. Obviously, the experiments will involve also third laboratory (Multi-lab) which will be used to generate thermal and electrical profiles to be supplied by PV integration or Exchange lab.