Climate and cultural based design and market valuable technology solutions for Plus Energy Houses

Report on multi-system control strategies for HMS

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Executive summary

The optimization of the control strategy of the energy system of a building is crucial to increase the performance of the building and reduce the electrical energy withdrawn from the electrical grid. In this report the optimization of a control strategy for a residential building is described. The starting point is a rule-based control strategy that harmonizes the different technologies that compose the energy system.

The optimization consists in changing the setpoint of the thermal energy storage for the domestic hot water preparation and the dwellings' setpoint for space heating and space cooling to reduce the electrical energy withdrawn from the grid and increase the self-sufficiency and self-consumption of the energy system. The optimization logic is based on a daily forecast of the energy consumption of the building and the daily forecast of PV system's electricity generation. Both predictions are made according to the weather forecast (daily average temperature and daily global horizontal radiation). In order to provide more thermal inertia to the energy system and enhance flexibility, the thermal energy storage for domestic hot water preparation was tripled in size compared to the size suggested by technical standards. This allows to reduce the number of charging and discharging cycles within a day and increase the energy that can be stored.

The rule-based control logic that harmonizes the different technologies implemented in the energy system and the building, proved to be effective in guaranteeing sufficient levels of thermal comfort and environmental air quality. The control was tested with annual dynamic simulations performed in TRNSYS. The control was implemented on an energy system powered by a centralized heat pump and a photovoltaic system coupled with an electrical storage. The energy system was applied to two building archetypes, a low-rise multifamily house with 7 apartments, divided on three floors, and a high-rise multifamily house with 40 apartments divided on seven floors. The other technologies that were incorporated in the control are ceiling fans for air movement, venetian blinds for shading, decentralized mechanical ventilation units for air renewal and thermal energy storages.

These advanced control logics demonstrate that it is possible to shift the loads toward more favorable periods of the day by acting on few setpoint temperatures. The change of the setpoint to shift the loads increases the total electrical consumption because the COP of the heat pump gets lower. The load shifts have a positive impact on the system performance only when the additional consumption is covered by the PV system. In winter the self-consumption is high, meaning that the only way to further reduce the electricity withdrawn from the grid is to increase the size of the PV system. As in the reference building taken as example the roof and façade area capacity for PV

installation is fully exploited, the additional PV should be installed somewhere else, which might be not feasible. During spring and autumn, the thermal load is low, and it could be possible to avoid any withdrawal from the grid by increasing the size of the battery by 20%. In summer a positive balance is reached. However, during some days in which there is a lower PV production there is still the need to withdraw electricity from the grid.

In high efficient buildings over 50% of the total electrical loads is due to appliances and lighting. For this reason, a sophisticated control strategy is not always sufficient to reach a positive balance throughout the year. Energy efficient appliances and an optimal selection of their working period are crucial to reach the positive energy balance. For this reason, the building’s users should be aware of when it is convenient to use the appliances and when it is not the case.

The developed control strategies will be readapted and implemented in the cloud-based house management system (HMS) of AdvanticSys. More details about will be given in deliverable D3.2.

1 Introduction

The construction of energy efficient buildings and the adoption of high-performance HVAC system is crucial for the reduction of CO_2 emissions in the European residential building stock. The building sector consumes about 40% of the final energy consumptions and emits more than 30% of the greenhouse gas emissions in developed countries [1]. These figures have a direct impact on global warming, energy shortage and, in some cases, national security [2]. This concern has led to the establishment of various concepts, strategies, policies, standards, and regulations that aim to reduce building energy consumption and prompt sustainable construction. This can be achieved by improving building envelope design, using efficient and innovative technologies, and promoting the use of renewable energy to attain net, nearly zero, or plus energy buildings (PEB). In Cultural-E approach, a clear definition of PEB, including domain and time frame for the calculation, should include the concept of positive energy balance and a null contribution of consumed energy to CO2 emissions. In other words, the new building should be a sustainable prosumer [3].

The correct management of the building and the energy system that covers the loads of the building plays a crucial role as well. New construction buildings must comply to stricter construction regulations if compared to the past and the installation of renewable energy sources, such as photovoltaic system, is required. Nevertheless, the correct exploitation of renewable energy sources and the reduction of the electrical energy withdrawal from the grid are not an easy task to fulfill. To do so, the control of the building energy systems and other components must be harmonized to minimize the overall energy consumption. Besides having efficient components that can properly cooperate, it is also necessary to match the energy demand of the building and the energy system with the energy produced by the renewable energy sources.

The aim of this work is to define a rule-based multi-system control strategy that harmonizes the operation of an energy system with the technologies that are installed in the building. The starting point of this work are the solution sets for Plus Energy Buildings developed in the framework of H2020 Cultural-E project [4]. The considered solution set include an energy system which is powered by a centralized heat pump and a photovoltaic system coupled with an electrical storage. The energy system was tailored to two high building archetypes (low-rise multifamily house with 7 apartments divided on three floors and a high-rise multifamily house with 40 apartments divided on seven floors) with high performance envelope and four geo-clusters (Mediterranean, Continental, Oceanic and Sub-Artic). The other technologies that are considered in the solution set are ceiling fans for air movement, high-performance windows, venetian blinds for shading, decentralized mechanical ventilation units for air renewal, fan coils as emission units for space heating and space cooling and thermal energy storages.

A step forward was performed by implementing an advanced control strategy that aims at reducing the electrical energy withdrawn from the grid was defined. On top of this, some control logics for the energy sharing at neighborhood level were described. Finally, these control logics were merged in order to maximize the self-consumption and reduce the electrical energy withdrawn from the grid.

2 Description of the building and the energy system

The control strategy was implemented considering the reference buildings and solution sets for Plus Energy Buildings developed within H2020 Cultural-E project. A detailed description of the reference buildings, the solution sets and the boundary conditions can be found in Deliverable D4.3 “Repository of reference buildings models and related solution sets” [4]. In this document only a brief description of the building and the energy system is provided.

The model was specified for two different archetypes for new multifamily buildings (low-rise building and high-rise building) and four geo-clusters (Mediterranean, Oceanic, Continental, and Sub-arctic), thus creating eight different solution sets.

The solution sets include:

- High efficient envelope system (with characteristics adapted to the geo-cluster)
- Centralised heat pump (domestic hot water, space heating and space cooling)
- Decentralised mechanical ventilation units
- Fan coils as emission units for space heating and cooling
- Active shading system
- Ceiling fans
- Photovoltaic system

2.1 Description of building, implemented technologies and their control

Within the model, the spaces of the building are subdivided in thermal zones which are homogenous in terms of heating and cooling set point temperatures, ventilation air flow rate, internal gains, and destination of use. Each apartment of the Cultural-E reference buildings has been modelled in one or more thermal zones, finding a balance between accuracy of the simulation and simplicity of the model.

The low-rise building (Figure 1) is a 3-storeys building with 7 apartments (total net area of 663 m^2). Each apartment is divided into two thermal zone (day and night). Each zone has its own thermostat. However, for simplicity, the average temperature of the two zones is used to activate the heating and cooling units.

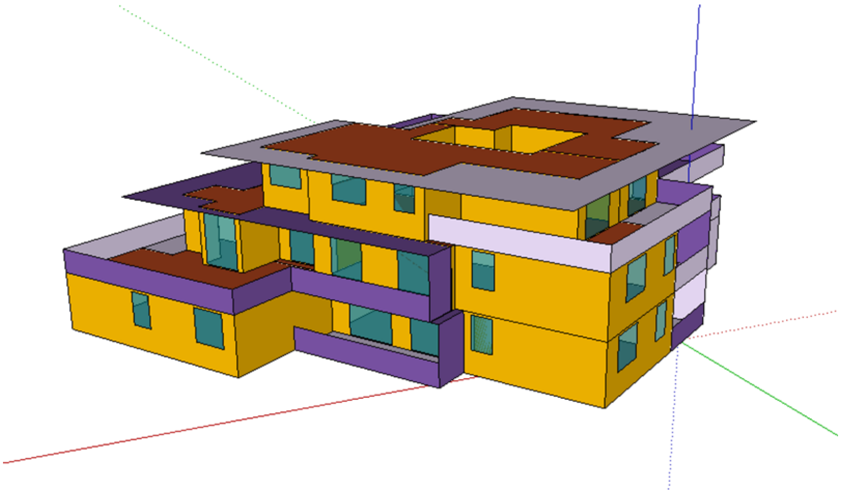


Figure 1. Low-rise building

The high-rise building (Figure 2) is a 7-storeys building with 6 apartments for each floor except for the ground floor that has 4 apartments (total net area of 2912 m^2). Each apartment is considered as a single thermal zone with one thermostat that is used to activate the heating and cooling units.

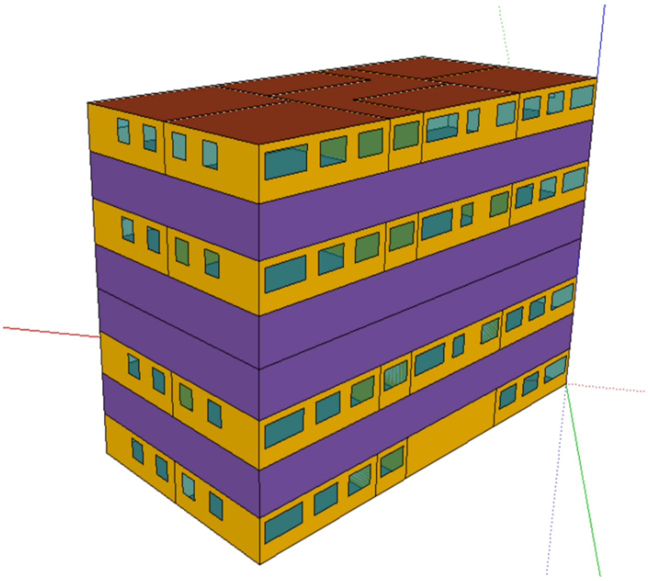


Figure 2. High-rise building

The envelope thermal properties have been defined in order to reach the design condition of new construction buildings. Hence, the transmittance values of all the types of structure (including windows) depend on the building location, which has its own regulation and climatic condition.

Table 1 reports the thermal transmittance values for the main envelope components in each geo-cluster.

Table 1. Envelop characteristics

Geo-cluster	Reference Country	U-VALUE External Wall [W/m²K]	U-VALUE Roof [W/m²K]	U-VALUE Ground floor [W/m²K]	U-VALUE windows [W/m²K]
Mediterranean	Italy	0.18	0.12	0.12	2.89
Continental	Germany	0.13	0.09	0.11	1.12
Oceanic	France	0.25	0.12	0.25	1.3
Sub Artic	Norway	0.10	0.08	0.09	0.76

The performed simulations use, as boundary conditions, the weather data of a typical year of the considered locations. For the Mediterranean climate, the weather data of Bologna were considered, Stuttgart is the reference location for the Continental climate, Brussel for the Oceanic climate and Oslo for the Sub-Artic climate. Meteorological files, taken from Meteonorm, include hourly values of a series of physical quantities, such as: dry bulb and dew point temperature, relative humidity, direct and diffuse solar irradiation, ground temperature, wind direction and speed and some others.

The set point temperatures for heating and cooling system (Table 2) are dependent on the location of the building and its climate. They have been provided by the project demo advisors based on users' expectations in each geo-cluster.

Table 2. Heating and cooling set-points for the different geo-clusters

Set Point	Mediterranean	Continental	Oceanic	Sub-Artic
Heating System [°C]	20	21	20	22
Cooling System [°C]	26	26	24	27

The internal gains due to presence of people, lightning and appliances are defined through a stochastic approach. A set of stochastic occupant behaviour profiles have been generated to represent the internal gains for each dwelling in the dynamic simulations. These profiles were differentiated for the different geo-clusters in accordance with cultural aspects.

Shading systems have been implemented into the model, regulating the amount of radiation passing through the windows and, therefore, the heat gain through the indoor environment. Venetian blinds (external and integrated in the glazing unit) with active control have been implemented in the Cultural-E active window system. The shading control logics are dependent on the indoor temperature conditions, the solar radiation, and the occupancy state of the room. As an example, following tables and figures describe the control strategies that have been implemented into the model for the Mediterranean geo-cluster for both shading systems.

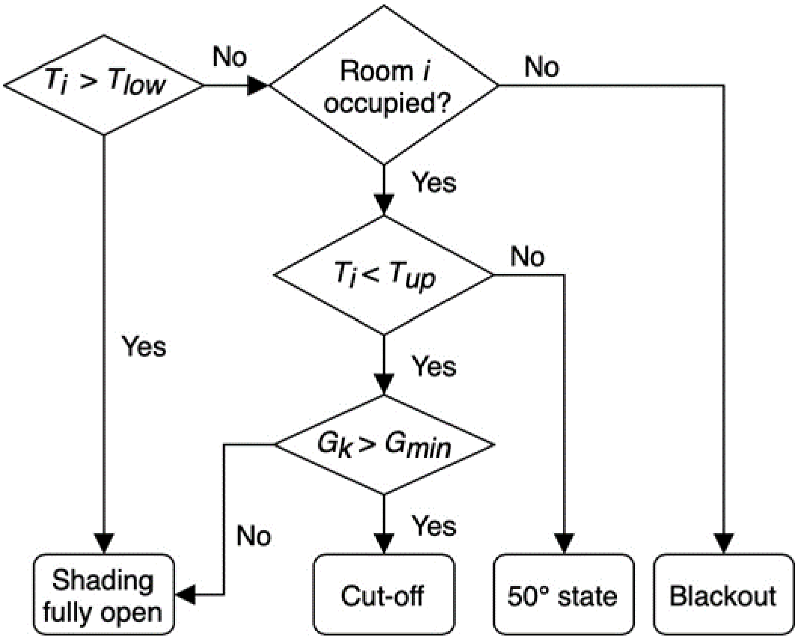


Figure 3. Decision tree for the shading system control.

Table 3. Parameters for the control of the shading system.

Parameter	External Venetian Blinds	Integrated Venetian Blinds
T_i	Thermal zone internal temperature	
T_{low}	22°C	22°C
T_{up}	26°C	25°C
G_k	Irradiance incident on facade	
G_{min}	300 W/m^2	300 W/m^2

Natural ventilation is set as complementary to the mechanical ventilation. For the day-time natural ventilation is activated when certain conditions are met:

- At least one person is present in the room/zone
- During summer, natural ventilation can be activated during daytime, while the outdoor temperature is included in a certain acceptable range (between 18°C and 24°C) and the indoor temperature is above a threshold (above 23°C). Additionally, during summer night-time, natural ventilation is activated to cooling down the building, thus, reducing the space cooling demand during the day
- During winter, natural ventilation is activated for thirty minutes in the morning, replicating the behaviour of the occupants, who usually want to have new fresh air in the apartments after the night.

The air change rate for natural ventilation is set to 2 vol/h.

The infiltration rate is defined as:

$$ACH_{inf} = K1 + K2 \cdot \left(T_{air,in} - T_{air,out}\right) + K3 \cdot v_{wind}$$

Where:

- K1 = 0.1
- K2 = 0.011
- K3 = 0.034

which are the parameter values considered for tight buildings. This equation can be found in the ASHRAE Handbook of Fundamentals (1989).

The decentralised mechanical ventilation units run when the natural ventilation is not active (windows are closed), having a constant airflow rate that is a characteristic of the ventilation machine (typical values used are in the range of 40-50 m^3/h). A heat recovery system, with an efficiency of 70%, is present in the machine. Figure 4 shows the control logic of the mechanical ventilation units.

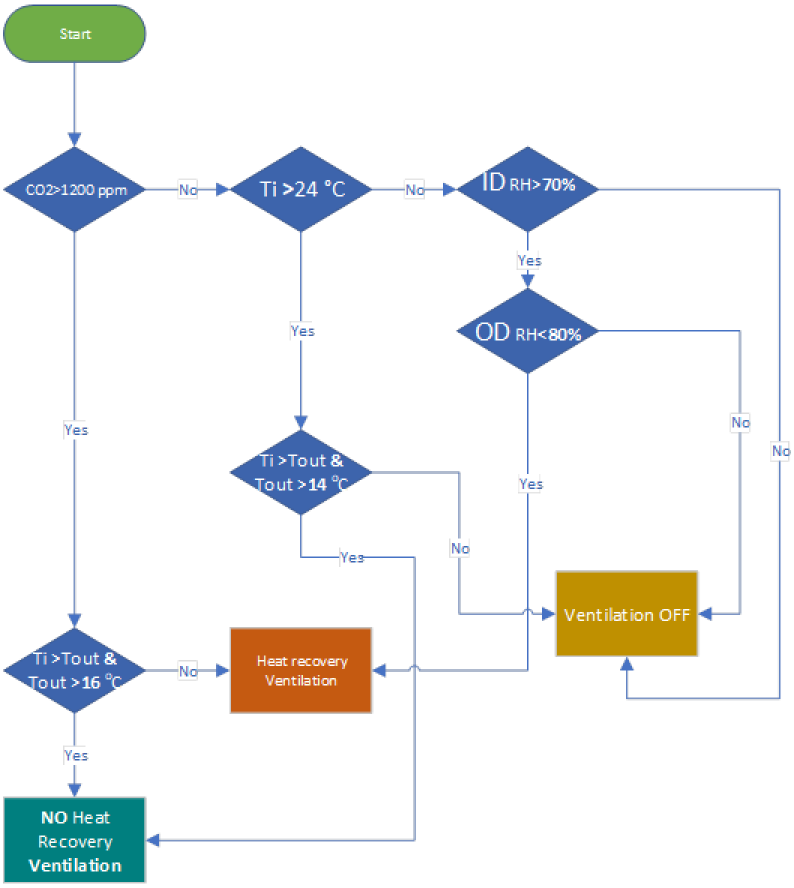


Figure 4. Decision tree for the ventilation system control.

The ceiling fans operation is emulated by shifting the indoor air setpoint for the building during the mid-seasons and summer. The aim is to reduce the space cooling load that the heat pumps should provide to the building without reducing the thermal comfort. To do so, the cooling setpoints are changed throughout the year. Some assumptions were made to simplify the implementation of the control in the simulation model:

- The speed of the fans is kept constant when the ceiling fans are activated
- The fans are activated if the internal air temperature exceeds the setpoint temperature (Table 2)
- The fans are not activated if there is natural ventilation or free night cooling
- The activation of the ceiling fans rises the setpoint of the hysteresis that regulates the hydronic space cooling (fan coils) by 1.8K (Babich et al., 2017 [5])
- When the ceiling fans are active, they consume a constant amount of electricity (30 W each)
- One ceiling fan for each thermal zone is considered

The photovoltaic system is composed by the PV panels, a battery to store the energy and a basic controller. The number of PV panels, their orientation and the capacity of the battery were defined in order to maximize the self-consumption of electricity based on the hourly electrical load profile of the different buildings defined with dynamic simulation in TRNSYS.

The PV panels and storage battery considered for the model are commercial items with specific characteristics, reported in Table 4.

Table 4. Characteristics of PV panels and battery

Voltage of panel at nominal condition	[V]	29.8
Current of panels at nominal condition	[A]	7.7
Power of panel at nominal conditions	[W]	229.8
Area of panel	[m^2]	1.6
Bandgap of semiconductor	[eV]	1.12
Charging efficiency of battery cells	[-]	0.85
Regulator efficiency	[-]	0.78
Inverter efficiency	[-]	0.98
Higher limit on state of charge of battery	[-]	0.90
Lower limit on state of charge of battery	[-]	0.10

Table 5 and Table 6 report the characteristics of the PV system for the low-rise and high-rise buildings in each geo-cluster.

Table 5. Characteristics of the PV system for the low-rise building in each geo-cluster

		Mediterranean	Continental	Oceanic	Sub-Artic
Nominal power on roof	[kW]	17.7	17.7	17.7	17.7
Slope of panels on roof	[°]	37.0	37.0	38.0	44.0
Azimuth of panels on roof	[°]	0.0	0.0	0.0	0.0
Number of panels on roof	[-]	77	77	77	77
Nominal power on SE façade	[kW]	9.4	9.4	9.4	8.5
Slope of panels on SE façade	[°]	90.0	90.0	90.0	90.0
Azimuth of panels on SE façade	[°]	-39.4	-39.4	-39.4	-39.4
Number of panels on SE façade	[-]	41	41	41	37
Nominal power on SW façade	[kW]	5.5	5.1	5.5	5.5
Slope of panels on SW façade	[°]	90.0	90.0	90.0	90.0
Azimuth of panels on SW façade	[°]	50.2	50.2	50.2	50.2
Number of panels on SW façade	[-]	24	22	24	24
Capacity of the battery	[kWh]	46.0	42.7	63.6	16.2

Table 6. Characteristics of the PV system for the high-rise building in each geo-cluster

		Mediterranean	Continental	Oceanic	Sub-Artic
Nominal power on roof	[kW]	34.0	34.0	34.0	34.0
Slope of panels on roof	[°]	44	44	44	44
Azimuth of panels on roof	[°]	0	0	0	0
Number of panels on roof	[-]	148	148	148	148
Nominal power on SE façade	[kW]	62.5	65.9	68.0	68.0
Slope of panels on SE façade	[°]	90	90	90	90
Azimuth of panels on SE façade	[°]	-55	-55	-55	-55
Number of panels on SE façade	[-]	272	287	296	296
Nominal power on SW façade	[kW]	0	39.7	39.7	39.7
Slope of panels on SW façade	[°]	90	90	90	90
Azimuth of panels on SW façade	[°]	35	35	35	35
Number of panels on SW façade	[-]	0	173	173	173
Nominal power on NW façade	[kW]	39.7	0	67.3	65.3
Slope of panels on NW façade	[°]	90	90	90	90
Azimuth of panels on NW façade	[°]	125	125	125	125
Number of panels on NW façade	[-]	173	0	293	284
Capacity of the battery	[kWh]	48.7	128.5	108.0	167.0

The azimuth of the panels is 0° for panels oriented toward south, -90° for panels oriented toward east and +90° for panels oriented toward west.

2.2 Energy system description

The energy system implemented in the solution sets is shown in Figure 5.

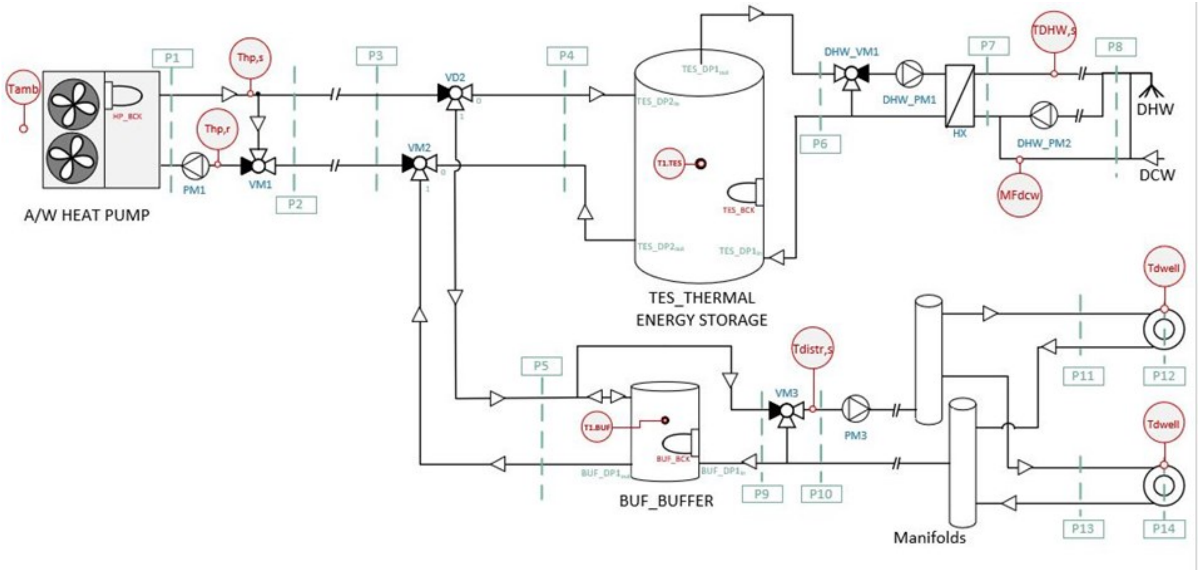


Figure 5. P&I diagram of the implemented HVAC system.

The heat pump generates heating and cooling power exploiting the outdoor air. At the load side of the heat pump, the operating fluid is water that is used both as energy vector and storage. The working fluid exiting the heat pump is sent to diverter VD2, that deflects the fluid towards the thermal energy storage (TES) or towards the buffer tank (BUF), according to the operating scheme of the heat pump. The TES is the thermal storage for domestic hot water. The BUF acts as hydraulic separator between generation and distribution circuit for space heating and cooling. Moreover, the buffer tank is also used as small energy storage to provide some thermal inertia to the space heating and cooling distribution.

The heat pump is the only heat generator; thus, it should be sized to consider the contemporaneity of domestic hot water loads and space heating/cooling loads. The size of the heat pump is calculated as:

$$Qth_{HP} = (Qth_{DHW} + \max(Qth_{SH}, Qth_{SC})) \cdot HP_{sizing}$$

Where:

- Qth_{DHW} is the maximum thermal load of domestic hot water (determined with technical standard UNI 9182:2010)
- Qth_{SH} is the maximum thermal load of the building for space heating (determined with ideal heating simulation in TRNSYS)

- Qth_{SC} is the maximum thermal load of the building for space cooling (determined with ideal cooling simulation in TRNSYS)
- HP_{sizing} is the saying coefficient of the heat pump (imposed equal to 0.7)

The activation of the heat pump in domestic hot water mode is based on a hysteresis of a temperature sensor placed in the TES. When the temperature in the TES storage, at sensor T1.TES (placed at 60% of storage's height) falls below 45°C, the heat pump is activated in domestic hot water mode, with a temperature setpoint equal to 55°C. The heat pump generates warm water until the temperature at sensor T1.TES reaches 50°C. The distribution circuit for the domestic hot water is composed by a primary circuit and a secondary circuit, separated by a heat exchanger in order to separate the clean water coming from the water mains from the technical water circulating in the HVAC system. The primary circuit is composed by a circulating pump and a mixing valve. These two components modulate the mass flow rate and the temperature in the primary circuit to guarantee the correct temperature at the secondary circuit. The secondary circuit is composed by a circulating pump, a tee for the introduction of fresh water from the water main and a recirculation pipe. In the secondary circuit the water coming from the mains is mixed with the recirculated water. The entire fluid is sent to the heat exchanger where it is heated up to 42°C. When there is no withdrawal from the mains there is a recirculation of water in both the primary and secondary circuits to keep the pips warm. The circulation pump in the secondary circuit processes a constant water volume of 270 kg/h. The additional water flow is not processed by the heat pump, but its motion is regulated by the pressure difference between the water mains and the distribution circuit. The domestic hot water distribution considers two columns to account for the thermal losses between the storage and the users.

The size of the thermal energy storage for domestic hot water (TES) depends on the minimum volume (calculated according to technical standard UNI 9182:2010) and the position of the sensor T1.TES (temperature sensor at which the DHW hysteresis for the activation of the heat pump is applied). The minimum volume is the volume above the sensor T1.TES, as shown in Figure 6.

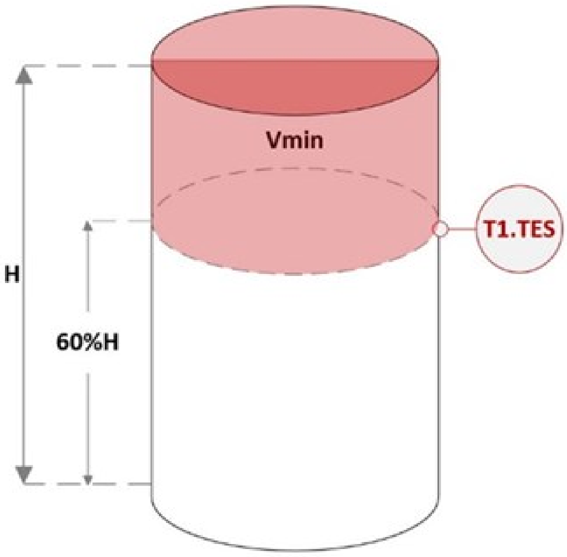


Figure 6. Thermal energy storage (TES) schematic.

The total volume of the TES is determined as:

$$V_{TES} = \frac{V_{TES,min}}{1 - H_{T1.TES}}$$

Where:

- $V_{TES,min}$ is the minimum volume of the TES (determined with technical standard UNI 9182:2010)
- $H_{T1.TES}$ is the normalized height of sensor T1.TES (imposed equal to 0.6)

The activation of the heat pump in space heating mode or space cooling mode is similar to the activation of the heat pump in domestic hot water mode. However, the setpoint of the sensor T1.BUF (also placed at 60% of total height) is variable. For the space heating, this sensor follows the climatic curve temperature that is imposed to the distribution temperature with a hysteresis of +0K and -3K. An example of climatic curve, dependent on the outdoor temperature and the emission units, is shown in Figure 7.

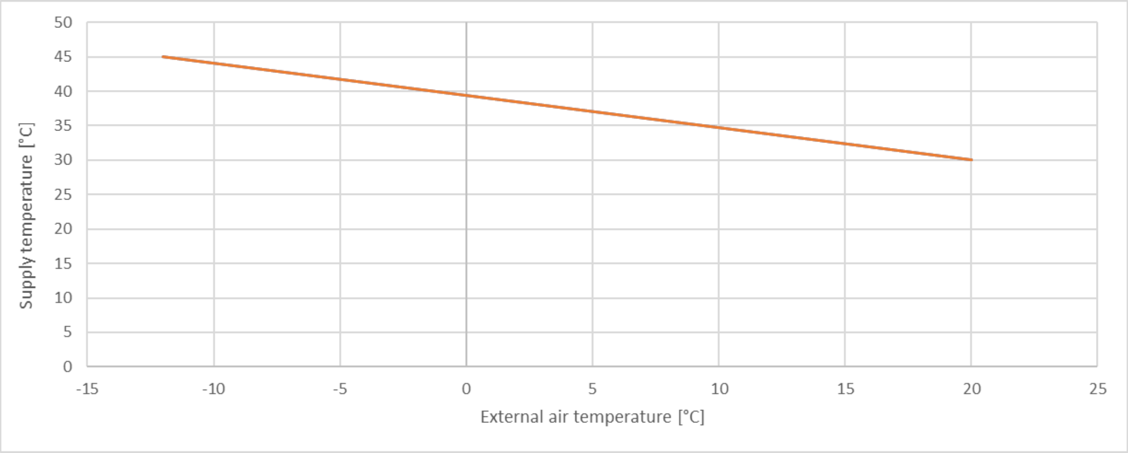


Figure 7. Example of a climatic curve.

The climatic curve applied to the supply temperature depends on the considered geo-clusters. The considered values are reported in Table 7

Table 7. Values used to build the climatic curve of each geo-cluster

Geo-cluster	$T_{amb,1}$ [°C]	$T_{amb,2}$ [°C]	$T_{distr,s,set,1}$ [°C]	$T_{distr,s,set,2}$ [°C]
Mediterranean	-5	20	45	30
Continental	-12	21	45	30
Oceanic	-8	20	45	30
Sub-Artic	-17	22	45	30

For space cooling, the setpoint temperature is constant and it depends on the emission units. The hysteresis has a dead band of +3K and -0K. The distribution circuit is composed by a mixing valve, a centralized circulation pump, the supply and return manifolds, piping, and emission units. The mixing valve regulates the supply temperature to the distribution (climatic curve in space heating and constant temperature in space cooling) by mixing the flow coming from the generation/storage units and the return flow from the dwellings. The circulation pump, coupled with the supply manifold, regulates the mass flow rate that is sent to each dwelling according to the needs. Each dwelling has one thermostat per thermal zone (two for the low-rise building and one for the high rise-building) that activate the emission units and determine whether the circulating pump should provide the mass flow to the dwelling or not. The thermostats have a setpoint temperature that depends on the solution set (see Table 2) and a dead band of +0.5K / -0K The mass flow rate processed by each emission unite, if active, is constant. The emission units implemented in the solution sets are fan coils.

The buffer tank is not designed to serve as water storage but mainly acts as hydraulic separator between the generation and the distribution. The buffer tank has a volume of 10 litres per kW of installed power of heat pump (Qth_{HP}).

The circulating pumps are sized according to the nominal water flow rate for each circuit, except for the circulating pump in the secondary circuit for DHW distribution that is sized for a constant mass flow rate of 270 kg/h. The nominal mass flow rates depend on the power that each circuit should be able to provide and the nominal temperature difference of each circuit.

3 Advanced control strategies at building scale (bottom-up approach)

In this chapter the development of the advanced control strategies at building level are presented. First the basic control that harmonizes the operation of the different components is presented. Later the optimization logics and the comparison among the different controls are presented.

The aim of the rule-based control is to operate the energy system and the other technologies to cover the domestic hot water, space heating and space cooling demand of the building while trying to minimize the thermal load. In this way it is possible to maintain quality in the different thermal zones the setpoint temperature and the indoor air that satisfy user's requirements.

The advanced control has the additional feature of increasing the synergy between the generation systems (heat pump and photovoltaic system), the storages and the building's technologies to reduce the electrical energy withdrawn from the grid and maximize self-sufficiency and self-consumption. The main idea is to act on the temperature setpoints of the thermal energy storage and the building to shifts the thermal loads toward the central part of the day when the electrical consumption can be covered by the PV production. To reduce the electricity withdrawal from the grid it is important to know if the production of the PV system for the next 24 hours is higher or lower than the electricity consumption of the building in the same time span. To check this, it is necessary to develop a model that predicts the electrical demand of the building and the electricity production of the PV system based on the weather forecast.

3.1 Rule-based control

The rule-base control is implemented to manage the operation of the different components of the heating and cooling system. More details on the methodology are presented in the following. The control strategy is aimed at prioritizing DHW production.

The storages are used as connection nodes between generation and distribution systems. Therefore, the control of generation is independent from the control of distribution. This approach makes the control strategy easy to be scalable and adaptable to different building typologies and system configurations.

The structure of the control rules consists of five elements listed in the following:

- **monitored variables**: information acquired from the monitoring system

- **hystereses**: elaboration of the acquisition signals in Boolean format. The hystereses, in thermal systems, is useful to avoid continuous oscillation between two states due to the nature of the system
- **schemes**: represent the working modes of the heating and cooling system. The schemes are defined as logical phrase of hystereses
- **modulations**: refers to pumps and valves and it is used to scale the control signal of the component. The modulation can be either a fixed value or a function of other independent variables (temperature or mass flow rate)
- **control signal**: command given to the devices to be controlled; it is the combination of schemes and modulations as show in the block diagram of Figure 8.

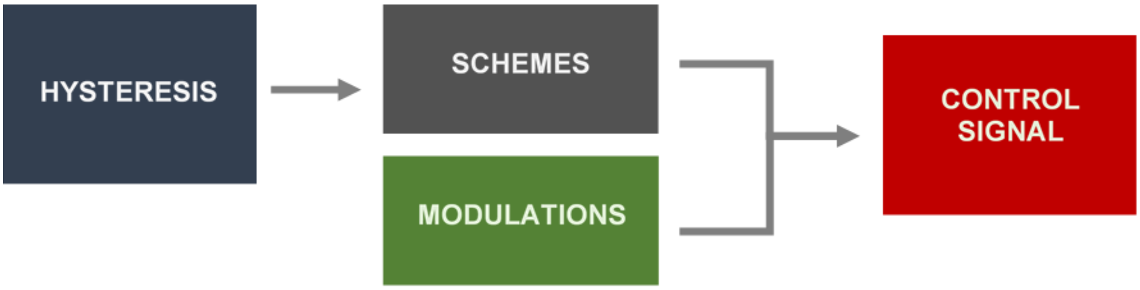


Figure 8. Block diagram for the structure of the control signal

3.1.1 Monitored variables

The measurements considered for the control of the system refer to air and water temperatures, water mass flow rate and irradiation on the horizontal plan. The position of the sensors in the HP system layout is shown in Figure 5. For the sake of clarity, the following nomenclature is used for the monitored variables:

- **Tamb**: External ambient air temperature
- **Thp,s**: supply temperature from the HP unit
- **Thp,r**: return (inlet) temperature to the HP unit
- **T1.BUF**: temperature of the small storage (buffer)
- **TDHW,s**: supply temperature to secondary circuit of the DHW distribution
- **Tdistr,s**: supply temperature to the distribution circuit for SH/SC
- **Tdwell**: internal air temperature of the dwelling used to activate the heating/ cooling system (only one temperature per dwelling is used for this purpose so that **Tdwell** represents the average between the temperatures of the two thermal zones of each apartment)

- **MFdcw**: mass flow rate of the DHW withdrawal (domestic cold water is entering in the recirculation system)
- **T1.TES**: temperature at top sensor of the TES used to maintain the upper part of the tank at a certain temperature for the DHW production.

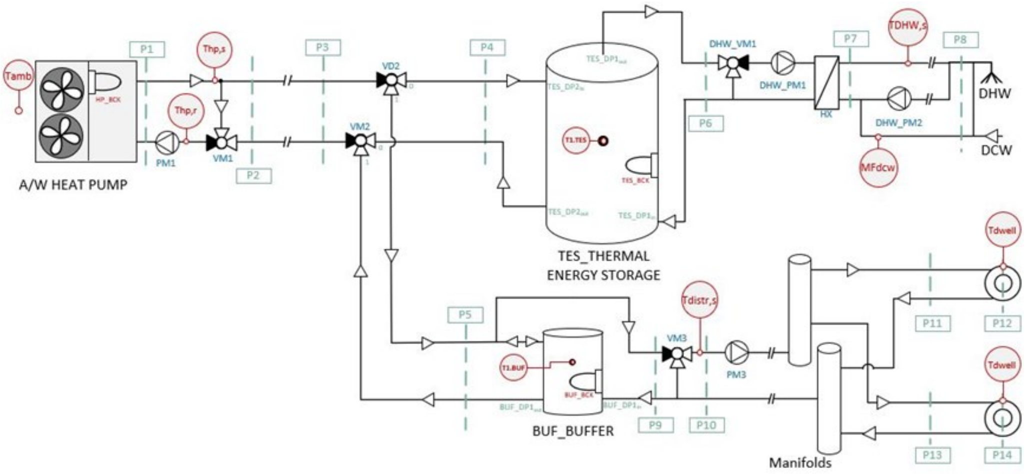


Figure 9. Monitored variables used in the control

3.1.2 Hystereses

Hysteresis is useful to reduce continuous oscillation of the control signal around a set value. It is referred to as a cooling process activation according to the scheme of Figure 10 (left). The consequence is that to reproduce the behavior of hysteresis for a heating process mode (on the right hand side of Figure 10), one has to negate the output (NOT(output)).

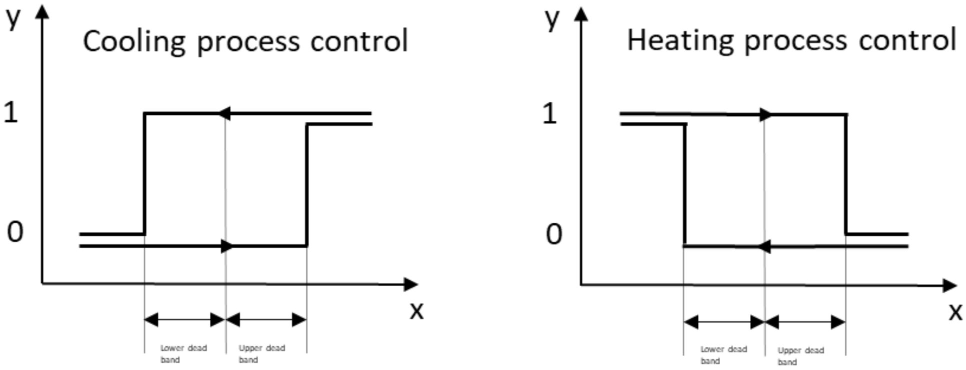


Figure 10. Schematization of the hysteresis controller for controlling a cooling or a heating process

The following signals represent the Boolean output of the hysteresis and are classified into four group categories:

- Signal **HA** comes from the hysteresis for controlling the Thermal Energy Storage use.
- Signals **HBa** and **HBb** come from the hystereses for controlling the buffer use in heating and cooling mode respectively.
- Signal group **HC** comes from the hysteresis used for controlling the DHW distribution side
- Signals **HDa** and **HDb** come from the hystereses for controlling the season (winter or summer operation of the system)
- Signals **HEa**, **HEb**, **HEc** and **HEd** come from the hystereses used to define the part of the day (day or night) to activate the setback
- Signals **HFa** and **HFb** come from the hystereses used to define the part of the day (day or night) to activate the back-up units
- Signal **HGa**, **HGb** and **HGc** come from the hystereses used for controlling the SH/SC distribution units of one dwelling. For each further distribution unit, the approach is identical using different nomenclature (from **HG** to **HM** for the low-rise building, 7 apartments, and from **HG** to **HV** for the low-rise building, 16 apartments)

3.1.3 Functional schemes

The working schemes of the HVAC system identify which are the “operating state” of the plant based on the hystereses state and output. A scheme identifies the operation condition of each of the subsystem components.

This paragraph describes the equations that define the combination of the hysteresis to individuate a scheme. The combination of hysteresis can be read in a logical way using the logic operator AND, OR and NOT. The result is that a functional scheme consists of the combination of Boolean signals (hysteresis output) and thus it is still a Boolean signal that can be either 0 (the scheme is not active) or 1 (the scheme is active).

3.1.3.1 Scheme 1 (S1): running the HP unit for DHW production

This scheme has been developed to activate the HP unit when it is required to charge the upper part of the TES. When the top tank sensor (T1.TES) measures a temperature below 45°C, the scheme is activated. Pumps and valves are oriented as shown in red in the below Figure 11.

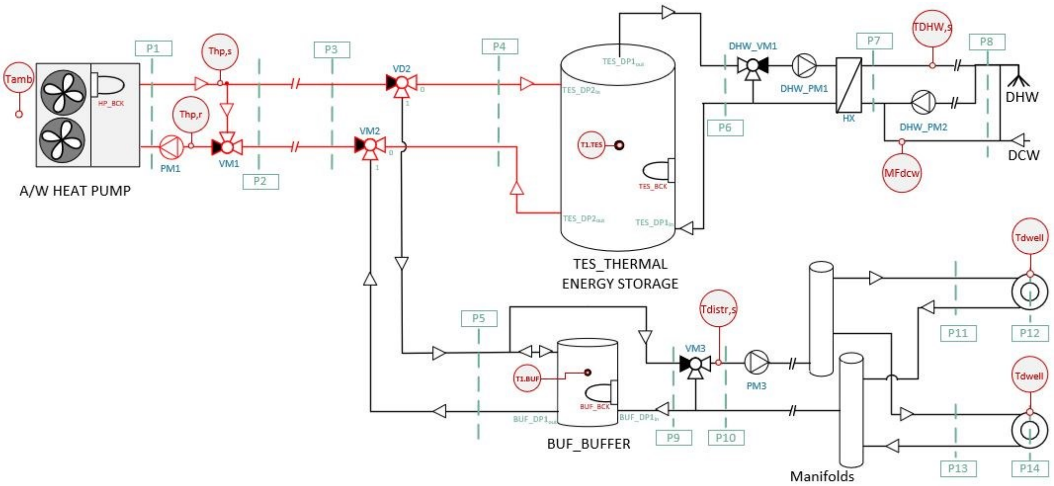


Figure 11. Circuits of the HP system activated during the operational scheme S1 (in red)

3.1.3.2 Scheme 2 (S2): running the HP unit for SH production in winter

This scheme is used to feed the buffer in winter (red line in Figure 12). This scheme is activated when there is no need of DHW preparation and the buffer temperature is lower than the setpoint defined by the climatic curve plus the lower dead band system (NOT(HBa)).

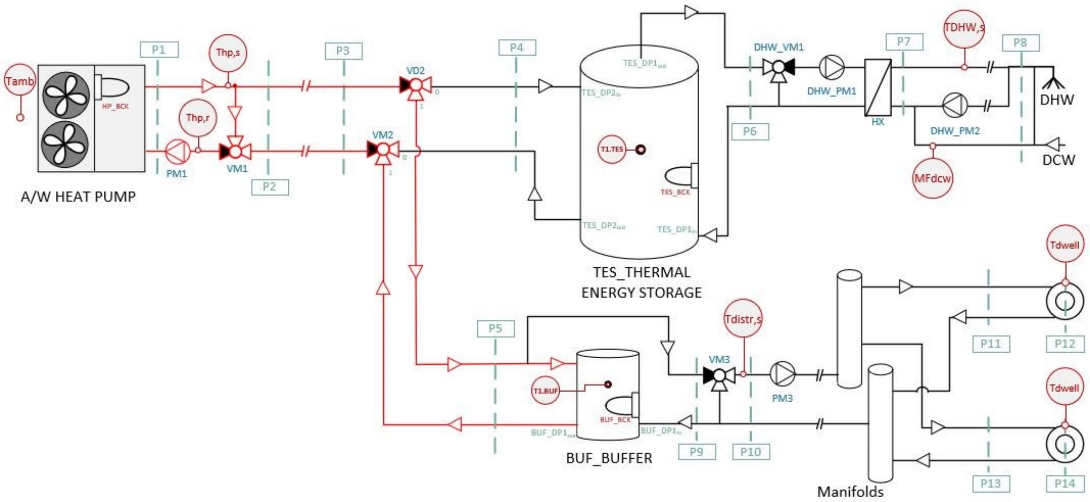


Figure 12. Circuits of the HP system activated during the operational schemes S2 and S3

3.1.3.3 Scheme 3 (S3): running the HP unit for SC production in summer

This scheme is used to feed the buffer in summer (red line in Figure 12) only whether the reversible HP system is coupled with an emission system that allow to provide both SH and SC (radiant floor). If S1 is not activated, the HP unit can be activated in cooling mode to cool down the BUF.

3.1.3.4 Scheme 4 (S4): DHW request

This scheme is structured to provide DHW to the user when required. The red circuit in the figure below takes the domestic cold water (DCW) coming from the main, with a withdrawal of at least 10 kg/h. The DCW water is heated up to a fixed supply temperature (42°C) through the heat exchanger and then supplied to the user. The scheme S4 is activated when the inlet (request) of DCW is detected in the distribution system by the mass flow meter (MFdcw shown in Figure 13).

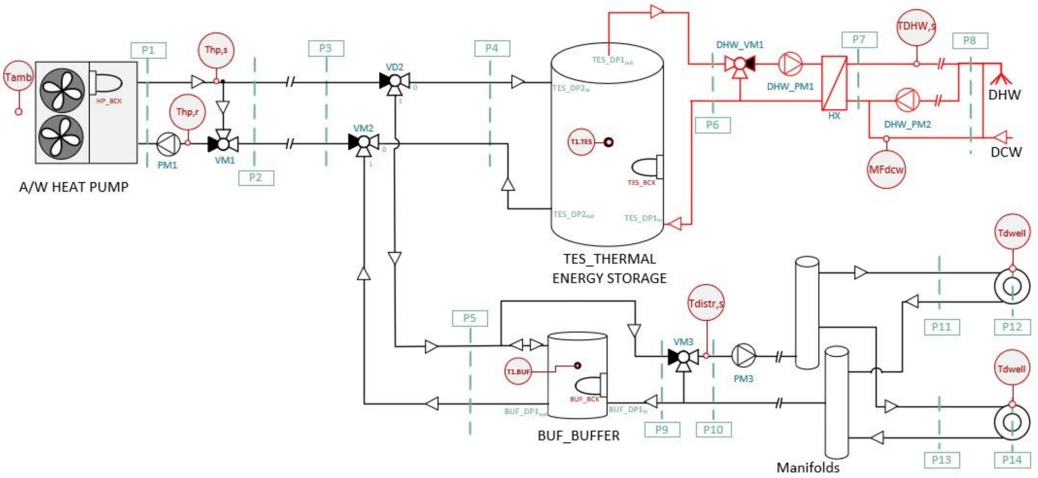


Figure 13. Circuits of the HP system activated during the operational scheme S4

3.1.3.5 Scheme 5 (S5): running the DHW recirculation system

Scheme 5 maintain active the recirculation scheme on the DHW circuit and involves the entire DHW distribution pipes. This scheme is used to keep all the parts of the circuit warm when there is not request of DHW as shown in Figure 14, allowing for a prompt delivery of DHW on demand.

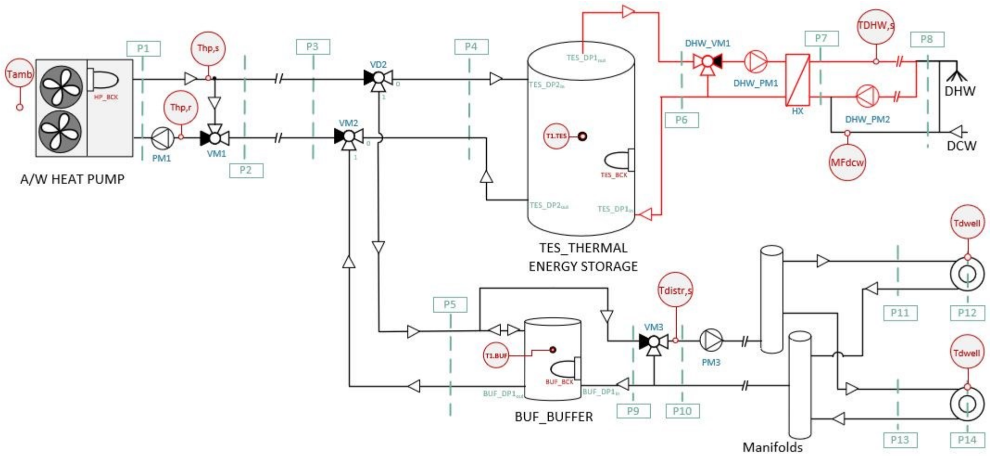


Figure 14. Circuits of the HP system activated during the operational scheme S5

3.1.3.6 Scheme 6a (S6a) and Scheme 6b (S6b): distribution unit for heating and cooling

These schemes are used to run the distribution units of the plant. One centralized pump regulates the water flow rate in the distribution, according to the number of dwellings that require either space heating or space cooling, to maintain a comfort temperature in the zones. For simplicity, only the schemes for one dwelling are reported. However, the same schemes are implemented for each dwelling.

When, in winter, the temperature drops below the setpoint S6a is activated. However, this happens only if the windows are closed. The opening of the windows is detected with a sensor that returns a 0-1 signal. If the windows are open the setpoint is decreased by 2 K. In winter it is possible to activate a night set-back period, during which the setpoint is reduced by 2 K.

When in summer the temperature rises above the setpoint S6b is activated. When the ceiling fans are activated, the cooling setpoint is raised by 1.8 K. In winter, valve VM3 regulates the supply temperature to the distribution according to the climatic curve. In summer valve VM3 keeps the supply temperature constant.

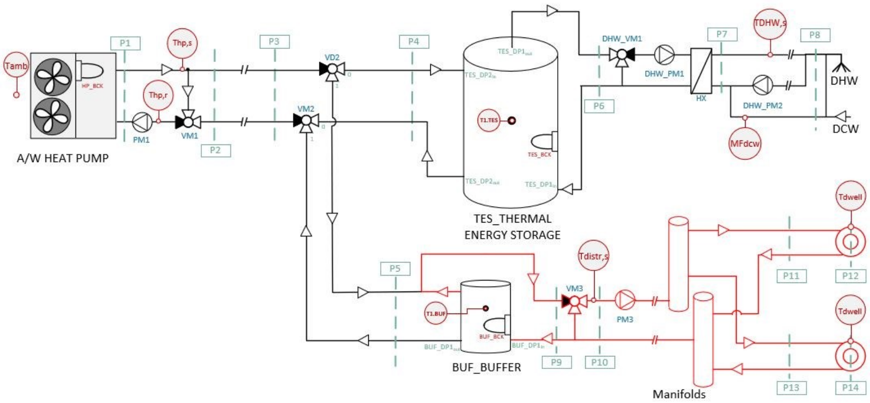


Figure 15. Circuits of the HP system activated during the operational schemes S6a and S6b

The combination of the scheme that activates the heat pump in SH and SC mode (schemes S2 and S3) with the activation of the distribution system (schemes from S6a/S6b to S12a/S12b or S21a/S21b), generates a further circuit, as can be seen in Figure 16. The fraction of the fluid that bypasses the buffer and goes directly to the distribution is computed to balance the mass flow on the generation and distribution circuits.

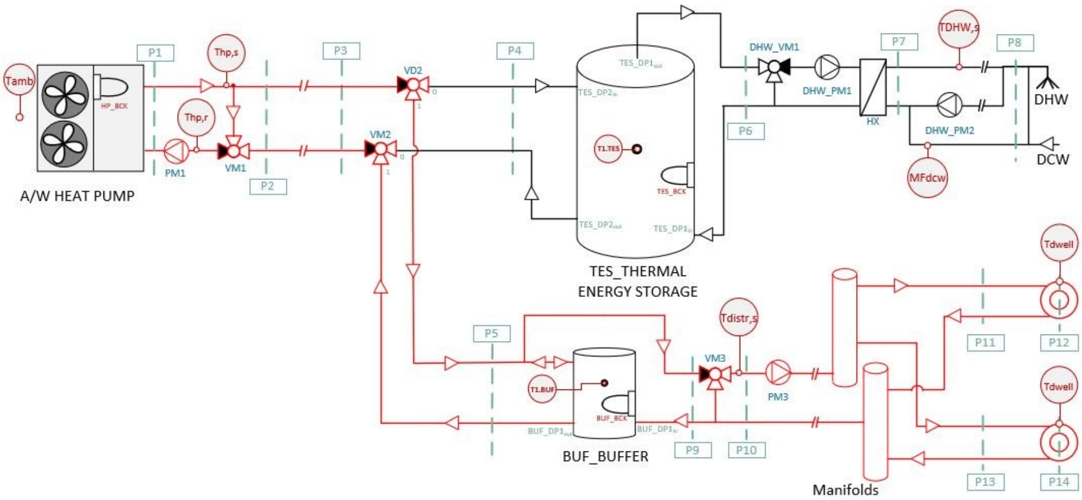


Figure 16. Circuits of the HP system activated during the operational schemes S2/S3 in combination with schemes S6a/S6b – S12a/S12b or S21a/S21b

3.1.4 Modulations

The activation signal of working schemes can be either 0 or 1, but for some component this information is not enough. Modulation scales the Boolean signal according to component's requirement in order to have a delivered signal that is between 0 and 1 (e.g. to control a variable speed pump).

3.1.4.1 Modulation of mass flow rate entering the heat pump

This modulation defines the mass flow rate that is circulating in the loop between the heat pump and the storages (TES and BUF). In real applications this circulating pump might be incorporated in the heat pump. This modulation aims at maintaining a constant temperature difference of 5°C between the inlet and the outlet of the generation device. However, this modulation only ranges between a minimum and a maximum, according to the characteristics of the circulation pump. The nominal mass flow rate, that determines the selection of the pump, is defined as a function of the nominal thermal power of the heat pump and the reference temperature difference (Table 8).

Table 8. Nominal HP size and mass flow rate of load side for the three reference buildings

Geo-cluster	Building typology	Heat pump size [kW]	Rated flow rate at load side [kg/h]
Mediterranean	Low-rise	43.9	7555.4
Continental	Low-rise	46.3	7969.2
Oceanic	Low-rise	42.7	7343.9
Sub-Artic	Low-rise	51.4	8837.5

Mediterranean	High-rise	145.6	25048.8
Continental	High-rise	143.0	24601.9
Oceanic	High-rise	162.9	28028.6
Sub-Artic	High-rise	116.8	20085.5

3.1.4.2 Modulation of mass flow rate and temperature in DHW distribution circuit

When there is DHW demand on the user side, the modulation on the circulation pump regulates the mass flow rate in the primary circuit of the DHW distribution to maintain a constant temperature drop of 15°C for the fluid entering the heat exchanger. However, the modulation is limited by the minimum and maximum flow rates that the pump can deliver.

Another modulation performed with a mixing valve defines the correct temperature setpoint in the primary circuit of DHW distribution that guarantees to maintain the setpoint temperature at the secondary circuit of DHW distribution.

On the secondary circuit of the DHW distribution the circulating pump DHW_PM2 is only used to recirculate a given mass flow rate to keep the circuit on temperature. This is because in this system, when there is DHW demand, the flow rate is defined by the pressure difference between the circuit and the water mains. Thus, the circulating pump DHW_PM2 always runs at a constant speed.

3.1.4.3 Modulation of mass flow rate and temperature in SH/SC distribution circuit

The circulating pump PM3 defines the mass flow rate in the SH/SC distribution circuit. Its modulation is computed according to the number of emission units that are operating. A manifold splits the flow to be distributed to each emission unit. Each emission units requires a constant mass flow rate when there is a demand of space heating or space cooling.

M_MF_0F1 defines the mass flow rate that flows in the emission units of apartment 0F1. The same kind of modulation is performed for each dwelling. These modulations are then used to define the control signal for the circulating pump PM3 and the fraction of flow flowing in branch of the manifold.

The power delivered to the building is performed by modulating the distribution temperature. This modulation on the distribution temperature is performed by acting on mixing valve VM3. The modulation of the valve is made in order to follow the setpoint for the distribution temperature, defined, in winter, by a climatic curve:

$$M\_Tclimatic\ =\ (((WEA\_TAMB - X1) * (Y2 - Y1)/(X2 - X1)) + Y1) \qquad (1)$$

Where:

- $WEA_TAMB$is the external ambient temperature [°C]
- $X1$, $X2$, $Y1$ and $Y2$ are the parameters that define the climatic curve (see Table 7)

In summer the distribution temperature is kept constant.

3.1.4.4 Modulation of mixing valve VM1

The mixing valve VM1 is used as a safety device for the heat pump. It is used to guarantee that the fluid entering the heat pump on the load side is within the operating range of the heat pump to avoid problems during the activation period. During the normal operation of the system this valve should remain closed.

3.1.5 Control signals

The control signals delivered to the components are the combination of schemes and modulations. For each element of the plant (pumps, valves, and generation device) there is a specific combination of schemes and modulation that define its modulation.

3.1.5.1 Control signals to the heat pump

The generation device receives an input when there is the need of heating up the TES, the buffer during winter or cooling it down during summer. These three control signals define when the heat pump should start and in which modulation. In many commercial heat pumps, it is not possible to define the DHW and SH mode separately.

Another control signal needed is the setpoint temperature, which is the temperature that the heat pump should provide to the TES and the BUF.

For the DHW mode the setpoint is equal to the TES setpoint plus the upper dead band of the hysteresis. However, in order to speed up the charging of the TES this temperature is increased (by 3-5 K) even if this decreases the performance of the heat pump because there should be quick response of the heat pump to the DHW demand.

For SH and SC the respond of the heat pump to the demand can be slower. Therefore, the setpoint of the heat pump in space heating mode is equal to the climatic curve used for the distribution plus 2 K to account for the thermal losses. The same is valid for the space cooling setpoint but is this case the temperature is decreased by 2 K.

3.1.5.2 Circulating pump and valves at the load side of the HP

The pump of the generation side is activated whenever the generation device is on. This signal is sent to the circulating pump PM1, that defines the mass flow rate entering the heat pump. If the heat pump has an internal circulating pump powerful enough to guarantee the correct mass flow rate, this control signal is not necessary as PM1 would not be implemented in the system.

Another control signal is sent to diverter VD2. This diverter is used to deflect the fluid exiting the heat pump towards the TES or the BUF. When this signal is equal to 0, the fluid is sent to the TES, when this signal is equal to 1, the fluid is set to the BUF and the SH/SC distribution circuit.

When the temperature of the fluid entering the heat pump is outside the working range of the heat pump, mixing valve VM1 mixes the incoming flow with the fluid exiting the heat pump. Usually, this safety device is already included in the heat pump.

3.1.5.3 Circulating pumps and mixing valve in DHW distribution circuit

The DHW distribution circuit has two circulating pumps, one on the primary (DHW_PM1) and one on the secondary (DHW_PM2).

The circulation pump DHW_PM1 is activated both when DHW is requested and when only recirculation is needed. However, the delivered mass flow rate is different for the two schemes. When there is DHW demand the pump must provide the mass flow rate that guarantees a constant temperature drop. When there is no DHW demand the pump runs at its minimum.

The circulation pump DHW_PM2 is always active and running at the minimum speed.

The control signal sent to mixing valve adjusts the position of the valve to find the correct temperature at primary circuit that guarantees the setpoint temperature in the secondary distribution temperature.

3.1.5.4 Circulating pump and mixing valve in SH/SC distribution circuit

The circulating pump PM3 defines the amount of fluid flowing in the SH/SC distribution circuit. This control signal combines the modulations of the flow rates for each apartment with the schemes for space heating and space cooling demand. Whenever there is the need of space heating or space cooling in a given room/dwelling, the correct mass flow rate is provided to the emission unit by modulating the circulating pump PM3.

The manifold receives the flow coming from the circulation pump PM3 and fractionate it to the different branches to be sent to the emission units of each apartment. Each fraction is computed as the mass flow rate of each dwelling divided by the total mass flow rate delivered by the circulating pump PM3.

Mixing valve VM3 mixes the fluid coming from the heat pump and the BUF with the fluid returning from the dwellings to match the setpoint temperature on the SH/SC distribution circuit. The control signal sent to mixing valve adjusts the position of the valve to maintain the correct temperature in the distribution circuit. The setpoint varies according to the period of the year. In winter the setpoint of the SH distribution is s variable climatic curve, while in summer the setpoint of the SC distribution is a constant value.

3.2 Optimization logics

The rule-based control has the advantage of being able to collect and elaborate several signals arriving from many components. Nevertheless, it is not possible to optimize the behavior of the entire system to minimize the energy consumption. Moreover, a simple rule-base control has very little flexibility and does not allow to match renewable energy production with the consumptions of the building.

For these reasons, a further development of the control is necessary. The proposed method merges the rule-based control with a simplified load predictor and PV production predictor. To maintain the control as simple as possible both load and PV production predictors are based on the weather forecast.

3.2.1 Simplified load predictor

The expected electrical load for the current day is calculated as a function of the daily heating degree days (HDD) during the heating season and the daily cooling degree days (CDD) during the cooling season. The HDD and CDD are computed by comparing the average daily temperature with a threshold temperature (20°C in winter and 15°C in summer).

$$HDD = MAX\left(20 - T_{air,ave,day}, 0\right)\ [°C * day]$$

$$CDD = MAX\left(T_{air,ave,day} - 15{,}0\right)\ [°C * day]$$

Table 9 summarizes the heating and cooling degree days for the different geo clusters.

Table 9. Heating degree days and cooling degree days for the different geo clusters

Geo cluster	HDD [°C*day]	CDD [°C*day]
Mediterranean	2290.5	1175.5
Continental	3333.3	285.3

Oceanic	2622.7	284.4
Sub-Artic	4325.4	168.1

With the results obtained with the rule-based control it was possible to correlate the daily HDD and daily CDD to the total daily electrical energy consumption of the building.

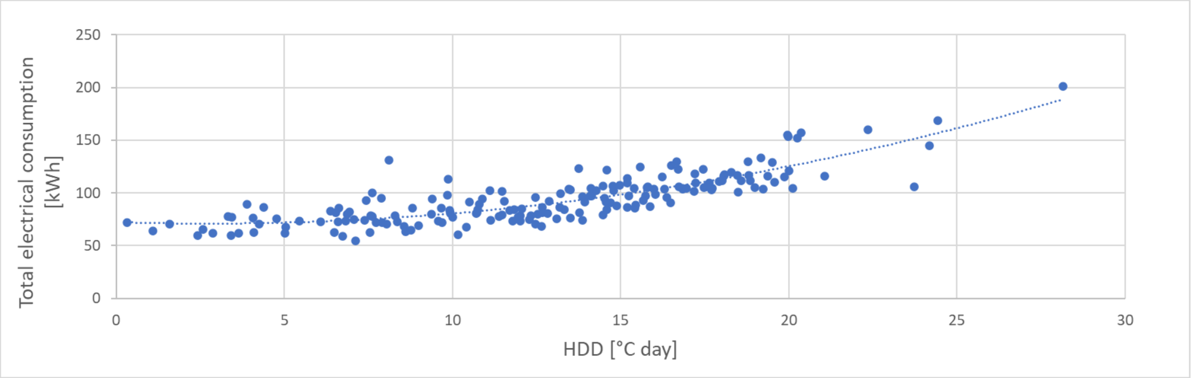


Figure 17. Correlation between daily HDD and total electrical consumption of the building (Low-Rise building in Mediterranean climate, winter operation)

Figure 17 shows the correlation between the daily heating degree days (HDD) and the total electrical energy consumption of the building for the Low-Rise building located in the Mediterranean climate during the winter operation. The data were fitted with a quadratic curve with a RMSE of 13%.

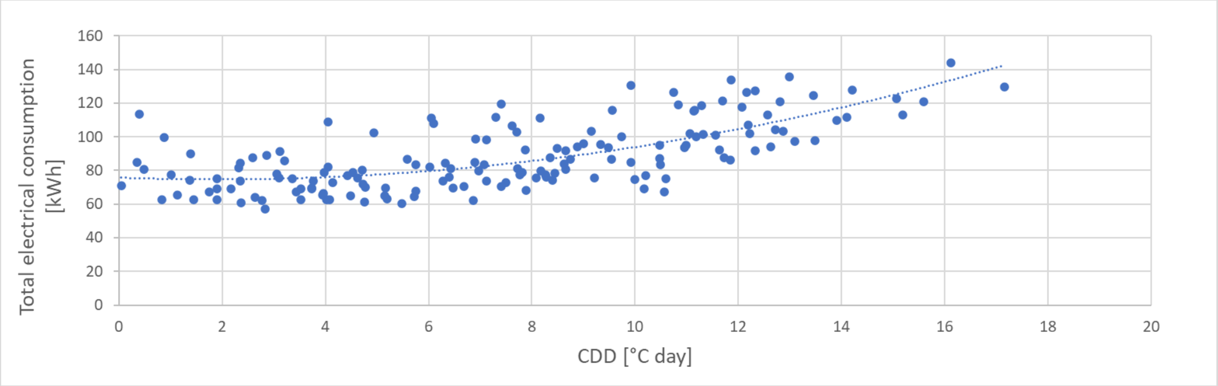


Figure 18. Correlation between daily CDD and total electrical consumption of the building (Low-Rise building in Mediterranean climate, summer operation)

Figure 18 shows the correlation between the daily cooling degree days (CDD) and the total electrical energy consumption of the building for the Low-Rise building located in the Mediterranean climate during the summer operation. The data were fitted with a quadratic curve with a RMSE of 18%.

It seems like it is possible to find a simple relationship between the HDD (or CDD) and the total electrical consumption. This relationship is however characteristic of each building. Therefore, the same approach was adopted for all the combinations of buildings and climate, in order to define the best fitting curve for each of them.

Figure 19 shows the comparison of daily electrical consumption calculated with the simulation model in TRNSYS and the predicted daily electrical consumption over one year of operation. The RMSE of this prediction is 15% if compared to the results of the complex simulation model.

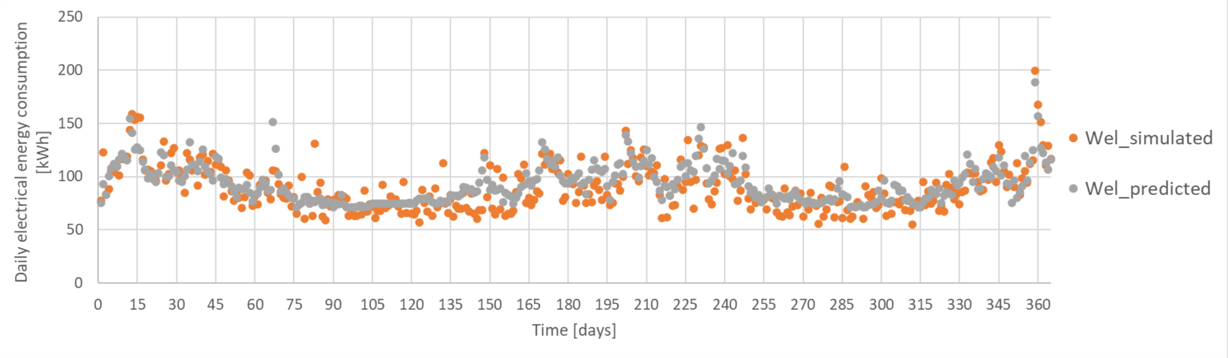


Figure 19. Comparison of daily electrical consumption calculated with the simulation model in TRNSYS and the predicted daily electrical consumption

During the winter operation of the system the total daily electrical consumption can be predicted as:

$$W_{el,predicted} = A_{0,H} + A_{1,H} \cdot HDD + A_{2,H} \cdot HDD^2 \; [kWh]$$

During the summer operation of the system the total daily electrical consumption can be predicted as:

$$W_{el,predicted} = A_{0,C} + A_{1,C} \cdot CDD + A_{2,C} \cdot CDD^2 \; [kWh]$$

Where:

- HDD are the forecasted daily heating degree days with base 20°C
- $A_{0,H}, A_{1,H}, A_{2,H}$ are the coefficients that correlate the daily HDD with the total daily electrical consumption during the winter operation (Table 10)
- CDD are the forecasted daily cooling degree days with base 15°C
- $A_{0,C}, A_{1,C}, A_{2,C}$ are the coefficients that correlate the daily CDD with the total daily electrical consumption during the summer operation (Table 10)

Table 10. Coefficients to predict the total daily electrical energy consumption of the building as a function of HDD in winter and CDD in summer

Geocluster	Building typology	$A_{0,H}$	$A_{1,H}$	$A_{2,H}$	$A_{0,C}$	$A_{1,C}$	$A_{2,C}$
Mediterranean	Low-rise	72.502	-1.008	0.183	74.754	1.015	0.185
Continental	Low-rise	65.253	-0.509	0.175	78.817	-0.755	0.101
Oceanic	Low-rise	98.146	-1.719	0.169	107.940	-1.945	0.358
Sub-Artic	Low-rise	84.275	-1.359	0.179	85.946	-0.014	0.041
Mediterranean	High-rise	257.330	-3.108	0.464	248.080	3.232	0.569
Continental	High-rise	227.900	3.345	0.311	275.920	3.780	0.098
Oceanic	High-rise	427.180	-10.479	0.579	435.230	-7.240	1.572
Sub-Artic	High-rise	340.270	-7.387	0.633	324.070	-9.291	1.521

3.2.2 Simplified PV production predictor

A similar approach was adopted to predict the daily electrical energy production of the PV system. In this the production of the PV system was correlated to the daily global horizontal radiation on the roof of the buildings.

Figure 20 shows the daily electrical energy production of PV system as a function of the daily global horizontal radiation on the roof for the High-Rise building located in the Sub-Artic climate. It is possible that there is a linear relationship between these two quantities, with a RMSE of 11%.

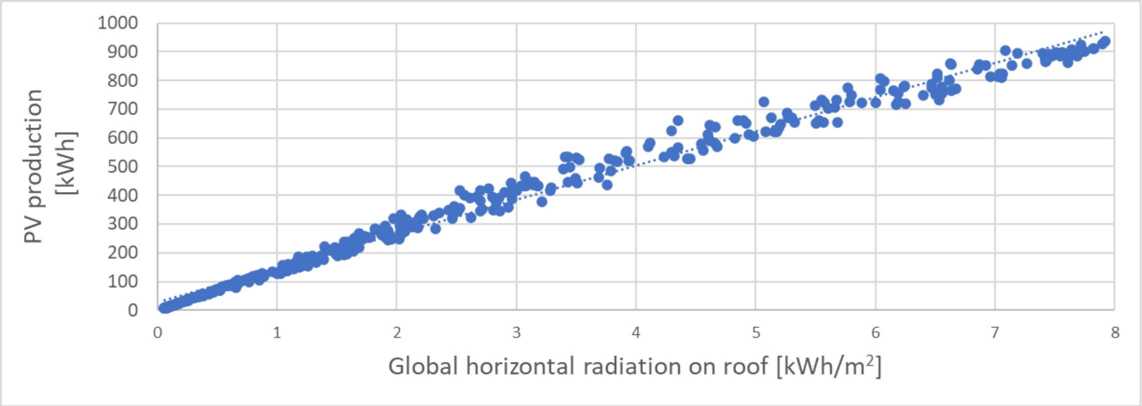


Figure 20. Daily production of PV system as a function of the daily global horizontal radiation on the roof (High-Rise building in Sub-Artic climate)

Figure 19 shows the comparison of daily electrical energy production of the PV system calculated with the simulation model in TRNSYS and the predicted daily electrical energy production of the PV system over one year of operation. The RMSE of this prediction is 9% if compared to the results of the complex simulation model.

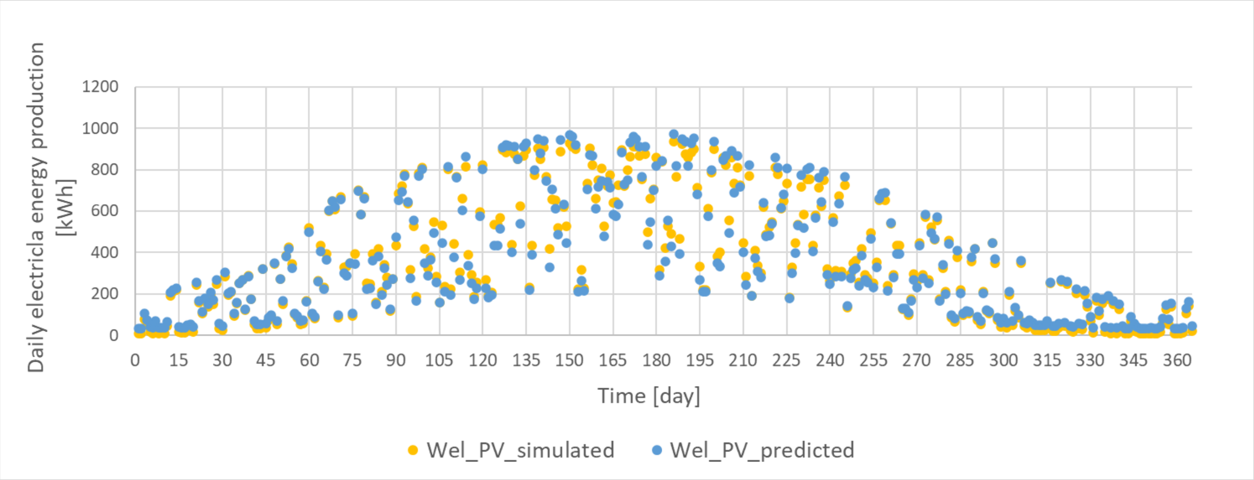


Figure 21. Comparison of daily electrical energy production of the PV system calculated with the simulation model in TRNSYS and the predicted daily electrical energy production of the PV system

The same approach was adopted for all the combinations of buildings and climate, in order to define the best fitting curve (linear curves passing through the origin) for each of them.

The daily electrical energy generated by the PV system can be predicted as:

$$W_{el,PV,predicted} = A_{1,PV} \cdot IT_{roof} \ [kWh]$$

Where:

- IT_{roof} is the foreseen daily global horizontal radiation on the roof
- $A_{1,PV}$ is the coefficient that correlates the daily global horizontal radiation on the roof with the total daily electrical energy generation of the PV system (Table 11)

Table 11. Coefficients to predict the total daily electrical energy consumption of the building as a function of HDD in winter and CDD in summer

Geo-cluster	Building typology	$A_{1,PV}$
Mediterranean	Low-rise	25.585
Continental	Low-rise	25.583
Oceanic	Low-rise	26.211
Sub-Artic	Low-rise	26.075
Mediterranean	High-rise	85.095
Continental	High-rise	96.379
Oceanic	High-rise	128.530
Sub-Artic	High-rise	124.734

3.2.3 Implemented control logics to increase the building's performance

The load predictor and the PV production predictor are used to modify some settings of the rule-based control to maximize the self-consumption and minimize the electrical energy withdrawn from the grid.

The settings that are modified in accordance to the predicted daily electrical energy consumption of the building and the predicted electrical energy produced by the PV system are:

- Setpoint of the thermal energy storage (T1.TES)
- Heating and cooling setpoints of the dwellings

Generally, increasing the setpoint of the thermal energy storage reduces the performance of the system for two reasons. A higher temperature in the storage means higher thermal losses through the envelope of the storage. Moreover, in order to increase the temperature in the storage it is necessary to increase the setpoint of the heat pumps. This implies a lower coefficient of performance (COP), thus, a higher consumption.

The thermal energy storage is usually charged during the first hours of the morning (between 6 AM and 9 AM) as during this period there is a higher users' demand. Unfortunately, in the morning the outdoor temperatures are lower, resulting in a lower COP, thus a higher electrical consumption. Moreover, in the morning the PV system produces a little amount of energy. Therefore, the almost the entire electrical energy is withdrawn from the grid. In order to increase the COP of the heat pump and decrease the withdrawal of electrical energy from the grid, it might be possible to charge the thermal energy storage only during the central part of the day, when the outdoor temperature is higher and the PV system produces more electricity. To do so, it is necessary to increase the size of the thermal energy storage (double the size as described in Par. 2.2). In this way it is possible to charge enough energy to cover the users' demand for an entire day and at the same time increase the flexibility of the system.

If the setpoint of the thermal energy storage is increased during the central part of the day to charge the storage in this time frame instead of in the first hours of the morning, the decrease of the COP due to a higher temperature at the load side of the heat pump is mitigated by the higher temperature at the source side of the heat pump. This effect is shown in Figure 22, where the performance map of a generic air-to-water heat pump is reported.

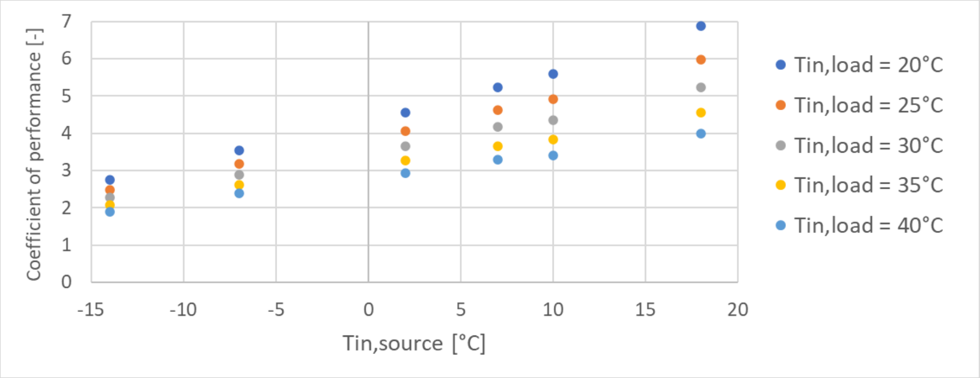


Figure 22. Performance map of a generic air-to-water heat pump

In addition to this, most of the electricity needed to run the heat pump in the central part of the day should be covered by the PV system.

For all this reasons it was decided to increase the setpoint of the thermal energy storage by 5 K only when:

1. The forecasted daily electricity production of the PV system is higher than the forecasted daily electricity consumption of the building
2. The outdoor temperature is 2 K higher than the forecasted daily average temperature

During winter, when a constant heating setpoint for the dwellings is used, most of the thermal demand is concentrated during the night and the first hours of the morning as there are lower temperature, thus higher thermal losses, and lower internal gains as people are not using appliances. This has a negative impact on the heating system's performance because the COP of the heat pump is lower (due to lower outdoor temperatures), and the PV system is not able to generate enough electrical energy to cover the load. Moreover, due to the climatic curve that is applied to the space heating distribution circuit the COP is lower during the colder hours of the day because the heat pump set point is higher.

In order to increase the performance, it is necessary to shift the load from the night/morning towards the central part of the day. This action would have has tree benefits:

1. The outdoor temperature is higher, thus the COP of the heat pump increases
2. The space heating climatic curve would require lower temperature, thus the COP of the heat pump increases
3. The PV system produces more electricity, thus the electrical energy withdrawn from the grid decreases

Moreover, to reduce the consumptions during the night a night set-back was introduced. From 10 PM to 6 AM the space heating setpoint is decreased by 2 K.

It was decided to increase the space heating setpoint of the dwellings by 2 K only when:

1. The forecasted daily electricity production of the PV system is at least half of the forecasted daily electricity consumption of the building
2. The outdoor temperature is 2 K higher than the forecasted daily average temperature

During summer, when a constant heating setpoint for the dwellings is used, most of the thermal demand is concentrated during the central part of the day because the outdoor temperature and the solar irradiation are higher. This has a negative impact on the heating system's performance because the energy efficiency ratio (EER) of the heat pump is lower (due to higher outdoor temperatures). However, in this part of the day the PV system is able to generate enough electrical energy to cover the load.

In order to increase the performance of the heat pump, it would be necessary to shift the load from central part of the day towards the first hours of the morning. Nevertheless, this means the load cannot be covered by the PV, thus the electricity withdrawn from the grid would increase. For this reason, it was decided not to focus on the shifting of the load but on the increase of the self-consumption.

It was decided to decrease the space heating setpoint of the dwellings by 2 K only when:

1. The forecasted daily electricity production of the PV system is higher than the forecasted daily electricity consumption of the building
2. The outdoor temperature is 2 K higher than the forecasted daily average temperature
3. The battery is fully charged

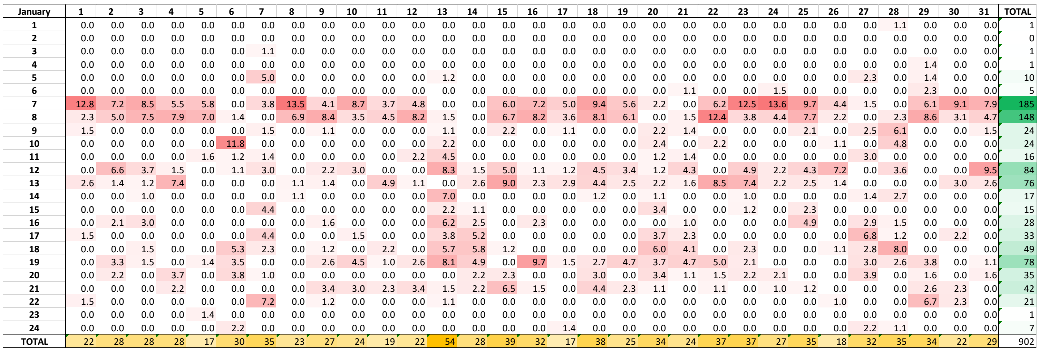
3.3 Summary of main results

In this chapter a comparison between different control strategies is reported, starting from the rule-based control strategy and arriving to the control strategy that implements the building's electrical energy consumption forecast and the PV system production forecast. For sake of simplicity only the results of the low-rise building located in the Mediterranean climate are reported. The analysis is focused on the hourly data of four reference months representing the different seasons. January for the cold heating season, March for the mild heating season, May for the mild cooling season and July for the hot cooling season. After this analysis the annual results for all the combinations of building archetypes and climates are reported, with a focus on some relevant KPIs.

3.3.1 Detailed analysis on Low-Rise building in Mediterranean climate

The starting point of the analysis are the building's loads in terms of domestic hot water preparation, space heating, space cooling and other electrical loads (appliances and lighting) with the rule-based control, considered as reference simulation for this analysis. All the presented results are hourly thermal or electrical energy expressed in kilowatt-hours (kWh).

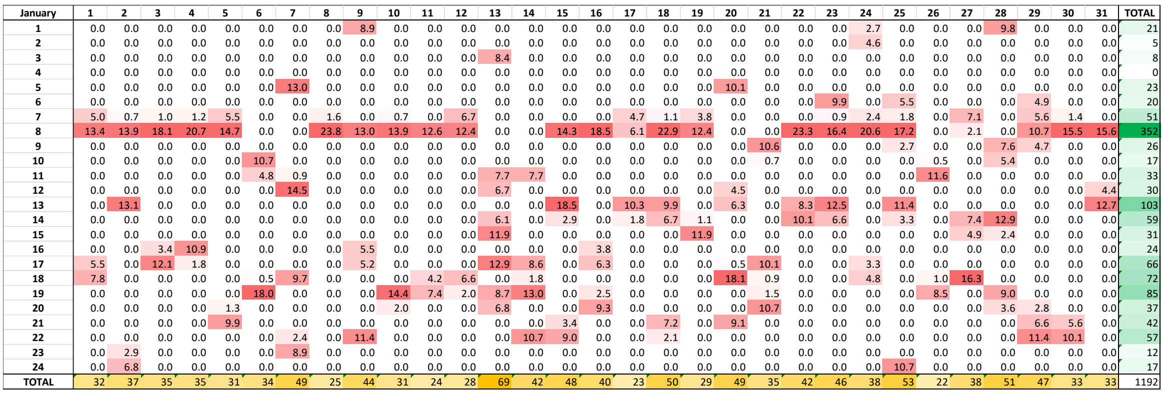
Figure 23 reports the hourly domestic hot water needs for the entire building in January. It is possible to notice that most of the load is concentrated in the first hours of the morning except for the weekend when the morning peak is delayed. Other relevant withdrawn are present around noon and in the evening. The load profile is very similar for all the months.



January	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	TOTAL
1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.1	0.0	0.0	0.0	1
2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0
3	0.0	0.0	0.0	0.0	0.0	0.0	1.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1
4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.4	0.0	0.0	1
5	0.0	0.0	0.0	0.0	0.0	0.0	5.0	0.0	0.0	0.0	0.0	0.0	1.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.3	0.0	1.4	0.0	0.0	10
6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.1	0.0	0.0	1.5	0.0	0.0	0.0	0.0	2.3	0.0	0.0	5
7	12.8	7.2	8.5	5.5	5.8	0.0	3.8	13.5	4.1	8.7	3.7	4.8	0.0	0.0	6.0	7.2	5.0	9.4	5.6	2.2	0.0	6.2	12.5	13.6	9.7	4.4	1.5	0.0	6.1	9.1	7.9	185
8	2.3	5.0	7.5	7.9	7.0	1.4	0.0	6.9	8.4	3.5	4.5	8.2	1.5	0.0	6.7	8.2	3.6	8.1	6.1	0.0	1.5	12.4	3.8	4.4	7.7	2.2	0.0	2.3	8.6	3.1	4.7	148
9	1.5	0.0	0.0	0.0	0.0	0.0	1.5	0.0	1.1	0.0	0.0	0.0	1.1	0.0	2.2	0.0	1.1	0.0	0.0	2.2	1.4	0.0	0.0	0.0	2.1	0.0	2.5	6.1	0.0	0.0	1.5	24
10	0.0	0.0	0.0	0.0	0.0	11.8	0.0	0.0	0.0	0.0	0.0	0.0	2.2	0.0	0.0	0.0	0.0	0.0	0.0	2.4	0.0	2.2	0.0	0.0	0.0	1.1	0.0	4.8	0.0	0.0	0.0	24
11	0.0	0.0	0.0	0.0	1.6	1.2	1.4	0.0	0.0	0.0	0.0	2.2	4.5	0.0	0.0	0.0	0.0	0.0	0.0	1.2	1.4	0.0	0.0	0.0	0.0	0.0	3.0	0.0	0.0	0.0	0.0	16
12	0.0	6.6	3.7	1.5	0.0	1.1	3.0	0.0	2.2	3.0	0.0	0.0	8.3	1.5	5.0	1.1	1.2	4.5	3.4	1.2	4.3	0.0	4.9	2.2	4.3	7.2	0.0	3.6	0.0	0.0	9.5	84
13	2.6	1.4	1.2	7.4	0.0	0.0	0.0	1.1	1.4	0.0	4.9	1.1	0.0	2.6	9.0	2.3	2.9	4.4	2.5	2.2	1.6	8.5	7.4	2.2	2.5	1.4	0.0	0.0	0.0	3.0	2.6	76
14	0.0	0.0	1.0	0.0	0.0	0.0	0.0	1.1	0.0	0.0	0.0	0.0	7.0	0.0	0.0	0.0	0.0	1.2	0.0	1.1	0.0	0.0	1.0	0.0	0.0	0.0	1.4	2.7	0.0	0.0	0.0	17
15	0.0	0.0	0.0	0.0	0.0	0.0	4.4	0.0	0.0	0.0	0.0	0.0	2.2	1.1	0.0	0.0	0.0	0.0	0.0	3.4	0.0	0.0	1.2	0.0	2.3	0.0	0.0	0.0	0.0	0.0	0.0	15
16	0.0	2.1	3.0	0.0	0.0	0.0	0.0	0.0	1.6	0.0	0.0	0.0	6.2	2.5	0.0	2.3	0.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0	4.9	0.0	2.9	1.5	0.0	0.0	0.0	28
17	1.5	0.0	0.0	0.0	0.0	0.0	4.4	0.0	0.0	1.5	0.0	0.0	3.8	5.2	0.0	0.0	0.0	0.0	0.0	3.7	2.3	0.0	0.0	0.0	0.0	0.0	6.8	1.2	0.0	2.2	0.0	33
18	0.0	0.0	1.5	0.0	0.0	5.3	2.3	0.0	1.2	0.0	2.2	0.0	5.7	5.8	1.2	0.0	0.0	0.0	0.0	6.0	4.1	0.0	2.3	0.0	0.0	1.1	2.8	8.0	0.0	0.0	0.0	49
19	0.0	3.3	1.5	0.0	1.4	3.5	0.0	0.0	2.6	4.5	1.0	2.6	8.1	4.9	0.0	9.7	1.5	2.7	4.7	3.7	4.7	5.0	2.1	0.0	0.0	0.0	3.0	2.6	3.8	0.0	1.1	78
20	0.0	2.2	0.0	3.7	0.0	3.8	1.0	0.0	0.0	0.0	0.0	0.0	0.0	2.2	2.3	0.0	0.0	3.0	0.0	3.4	1.1	1.5	2.2	2.1	0.0	0.0	3.9	0.0	1.6	0.0	1.6	35
21	0.0	0.0	0.0	2.2	0.0	0.0	0.0	0.0	3.4	3.0	2.3	3.4	1.5	2.2	6.5	1.5	0.0	4.4	2.3	1.1	0.0	1.1	0.0	1.0	1.2	0.0	0.0	0.0	2.6	2.3	0.0	42
22	1.5	0.0	0.0	0.0	0.0	0.0	7.2	0.0	1.2	0.0	0.0	0.0	1.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0	6.7	2.3	0.0	21
23	0.0	0.0	0.0	0.0	1.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1
24	0.0	0.0	0.0	0.0	0.0	2.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.2	1.1	0.0	0.0	0.0	7
TOTAL	22	28	28	28	17	30	35	23	27	24	19	22	54	28	39	32	17	38	25	34	24	37	37	27	35	18	32	35	34	22	29	902

Figure 23. Domestic hot water needs for entire building in January

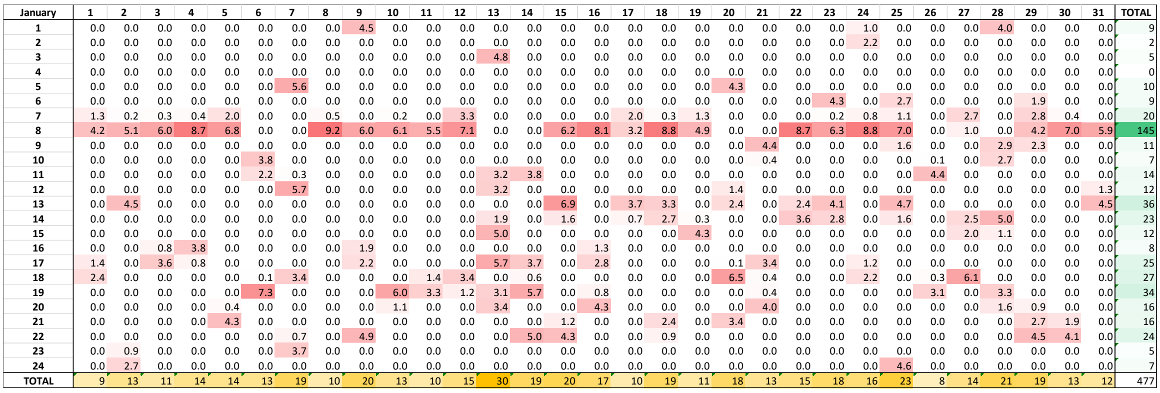
Figure 24 shows the hourly thermal energy generated by the heat pump for the preparation of domestic hot water in January. The profile is similar to the building needs profile. However, there is a small delay because of the thermal energy stored in the storage. The thermal energy generated by the heat pump is higher than the thermal need due to the thermal losses in the storage and the distribution circuit.



January	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	TOTAL
1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	8.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.7	0.0	0.0	0.0	9.8	0.0	0.0	0.0	21
2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	4.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	5
3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	8.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	8
4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0
5	0.0	0.0	0.0	0.0	0.0	0.0	13.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	10.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	23
6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	9.9	0.0	5.5	0.0	0.0	0.0	4.9	0.0	0.0	20
7	5.0	0.7	1.0	1.2	5.5	0.0	0.0	1.6	0.0	0.7	0.0	6.7	0.0	0.0	0.0	0.0	4.7	1.1	3.8	0.0	0.0	0.0	0.9	2.4	1.8	0.0	7.1	0.0	5.6	1.4	0.0	51
8	13.4	13.9	18.1	20.7	14.7	0.0	0.0	23.8	13.0	13.9	12.6	12.4	0.0	0.0	14.3	18.5	6.1	22.9	12.4	0.0	0.0	23.3	16.4	20.6	17.2	0.0	2.1	0.0	10.7	15.5	15.6	352
9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	10.6	0.0	0.0	0.0	2.7	0.0	0.0	7.6	4.7	0.0	0.0	26
10	0.0	0.0	0.0	0.0	0.0	10.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.7	0.0	0.0	0.0	0.0	0.5	0.0	5.4	0.0	0.0	0.0	17
11	0.0	0.0	0.0	0.0	0.0	4.8	0.9	0.0	0.0	0.0	0.0	0.0	7.7	7.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	11.6	0.0	0.0	0.0	0.0	0.0	33
12	0.0	0.0	0.0	0.0	0.0	0.0	14.5	0.0	0.0	0.0	0.0	0.0	6.7	0.0	0.0	0.0	0.0	0.0	0.0	4.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	4.4	30
13	0.0	13.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	18.5	0.0	10.3	9.9	0.0	6.3	0.0	8.3	12.5	0.0	11.4	0.0	0.0	0.0	0.0	0.0	12.7	103
14	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	6.1	0.0	2.9	0.0	1.8	6.7	1.1	0.0	0.0	10.1	6.6	0.0	3.3	0.0	7.4	12.9	0.0	0.0	0.0	59
15	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	11.9	0.0	0.0	0.0	0.0	0.0	11.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	4.9	2.4	0.0	0.0	0.0	31
16	0.0	0.0	3.4	10.9	0.0	0.0	0.0	0.0	5.5	0.0	0.0	0.0	0.0	0.0	0.0	3.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	24
17	5.5	0.0	12.1	1.8	0.0	0.0	0.0	0.0	5.2	0.0	0.0	0.0	12.9	8.6	0.0	6.3	0.0	0.0	0.0	0.5	10.1	0.0	0.0	3.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	66
18	7.8	0.0	0.0	0.0	0.0	0.5	9.7	0.0	0.0	0.0	4.2	6.6	0.0	1.8	0.0	0.0	0.0	0.0	0.0	18.1	0.9	0.0	0.0	4.8	0.0	1.0	16.3	0.0	0.0	0.0	0.0	72
19	0.0	0.0	0.0	0.0	0.0	18.0	0.0	0.0	0.0	14.4	7.4	2.0	8.7	13.0	0.0	2.5	0.0	0.0	0.0	0.0	1.5	0.0	0.0	0.0	0.0	8.5	0.0	9.0	0.0	0.0	0.0	85
20	0.0	0.0	0.0	0.0	1.3	0.0	0.0	0.0	0.0	2.0	0.0	0.0	6.8	0.0	0.0	9.3	0.0	0.0	0.0	0.0	10.7	0.0	0.0	0.0	0.0	0.0	0.0	3.6	2.8	0.0	0.0	37
21	0.0	0.0	0.0	0.0	9.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.4	0.0	0.0	7.2	0.0	9.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	6.6	5.6	0.0	42
22	0.0	0.0	0.0	0.0	0.0	0.0	2.4	0.0	11.4	0.0	0.0	0.0	0.0	10.7	9.0	0.0	0.0	2.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	11.4	10.1	0.0	57
23	0.0	2.9	0.0	0.0	0.0	0.0	8.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	12
24	0.0	6.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	10.7	0.0	0.0	0.0	0.0	0.0	0.0	17
TOTAL	32	37	35	35	31	34	49	25	44	31	24	28	69	42	48	40	23	50	29	49	35	42	46	38	53	22	38	51	47	33	33	1192

Figure 24. Thermal energy generated by the heat pump for DHW preparation in January

Figure 25 shows the hourly electrical energy consumed by the heat pump for the preparation of domestic hot water in January. It is possible to notice that most of the electrical consumption happens before 9AM or after 17PM when in January there is no sun, thus, the PV system is not able to cover the load.



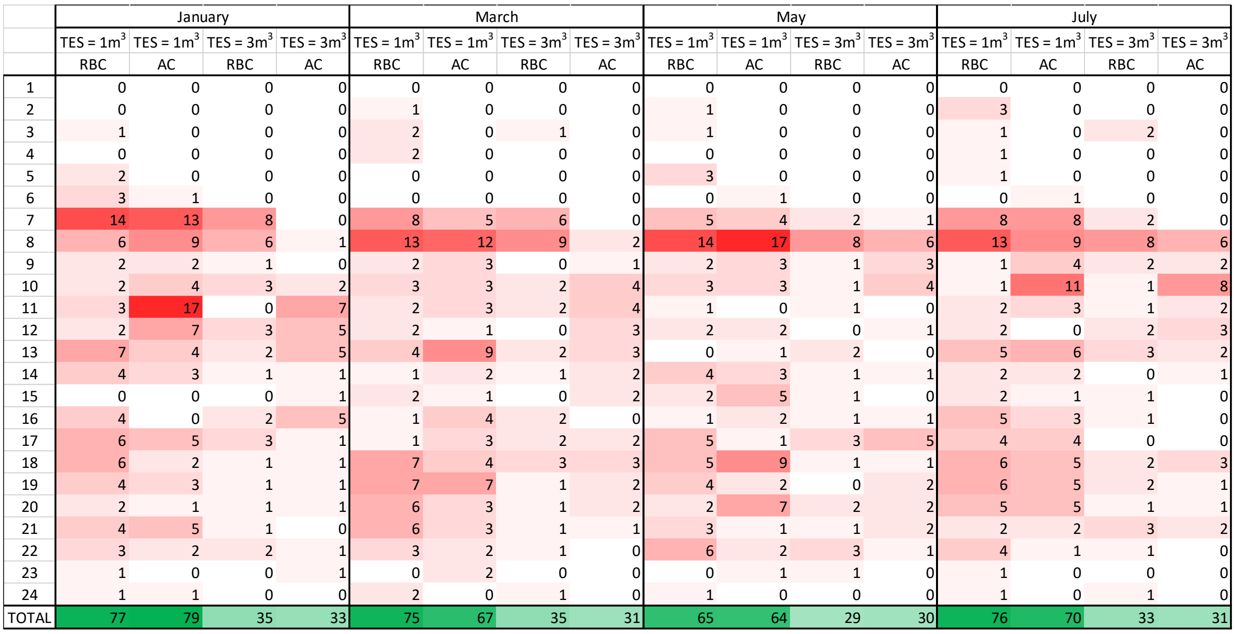
January	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	TOTAL
1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	4.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0	4.0	0.0	0.0	0.0	9
2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2
3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	4.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	5
4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0
5	0.0	0.0	0.0	0.0	0.0	0.0	5.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	4.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	10
6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	4.3	0.0	2.7	0.0	0.0	0.0	1.9	0.0	0.0	9
7	1.3	0.2	0.3	0.4	2.0	0.0	0.0	0.5	0.0	0.2	0.0	3.3	0.0	0.0	0.0	0.0	2.0	0.3	1.3	0.0	0.0	0.0	0.2	0.8	1.1	0.0	2.7	0.0	2.8	0.4	0.0	20
8	4.2	5.1	6.0	8.7	6.8	0.0	0.0	9.2	6.0	6.1	5.5	7.1	0.0	0.0	6.2	8.1	3.2	8.8	4.9	0.0	0.0	8.7	6.3	8.8	7.0	0.0	1.0	0.0	4.2	7.0	5.9	145
9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	4.4	0.0	0.0	0.0	1.6	0.0	0.0	2.9	2.3	0.0	0.0	11
10	0.0	0.0	0.0	0.0	0.0	3.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.4	0.0	0.0	0.0	0.0	0.1	0.0	2.7	0.0	0.0	0.0	7
11	0.0	0.0	0.0	0.0	0.0	2.2	0.3	0.0	0.0	0.0	0.0	0.0	3.2	3.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	4.4	0.0	0.0	0.0	0.0	0.0	14
12	0.0	0.0	0.0	0.0	0.0	0.0	5.7	0.0	0.0	0.0	0.0	0.0	3.2	0.0	0.0	0.0	0.0	0.0	0.0	1.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.3	12
13	0.0	4.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	6.9	0.0	3.7	3.3	0.0	2.4	0.0	2.4	4.1	0.0	4.7	0.0	0.0	0.0	0.0	0.0	4.5	36
14	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.9	0.0	1.6	0.0	0.7	2.7	0.3	0.0	0.0	3.6	2.8	0.0	1.6	0.0	2.5	5.0	0.0	0.0	0.0	23
15	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	5.0	0.0	0.0	0.0	0.0	0.0	4.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.0	1.1	0.0	0.0	0.0	12
16	0.0	0.0	0.8	3.8	0.0	0.0	0.0	0.0	1.9	0.0	0.0	0.0	0.0	0.0	0.0	1.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	8
17	1.4	0.0	3.6	0.8	0.0	0.0	0.0	0.0	2.2	0.0	0.0	0.0	5.7	3.7	0.0	2.8	0.0	0.0	0.0	0.1	3.4	0.0	0.0	1.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	25
18	2.4	0.0	0.0	0.0	0.0	0.1	3.4	0.0	0.0	0.0	1.4	3.4	0.0	0.6	0.0	0.0	0.0	0.0	0.0	6.5	0.4	0.0	0.0	2.2	0.0	0.3	6.1	0.0	0.0	0.0	0.0	27
19	0.0	0.0	0.0	0.0	0.0	7.3	0.0	0.0	0.0	6.0	3.3	1.2	3.1	5.7	0.0	0.8	0.0	0.0	0.0	0.0	0.4	0.0	0.0	0.0	0.0	3.1	0.0	3.3	0.0	0.0	0.0	34
20	0.0	0.0	0.0	0.0	0.4	0.0	0.0	0.0	0.0	1.1	0.0	0.0	3.4	0.0	0.0	4.3	0.0	0.0	0.0	0.0	4.0	0.0	0.0	0.0	0.0	0.0	0.0	1.6	0.9	0.0	0.0	16
21	0.0	0.0	0.0	0.0	4.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.2	0.0	0.0	2.4	0.0	3.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.7	1.9	0.0	16
22	0.0	0.0	0.0	0.0	0.0	0.0	0.7	0.0	4.9	0.0	0.0	0.0	0.0	5.0	4.3	0.0	0.0	0.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	4.5	4.1	0.0	24
23	0.0	0.9	0.0	0.0	0.0	0.0	3.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	5
24	0.0	2.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	4.6	0.0	0.0	0.0	0.0	0.0	0.0	7
TOTAL	9	13	11	14	14	13	19	10	20	13	10	15	30	19	20	17	10	19	11	18	13	15	18	16	23	8	14	21	19	13	12	477

Figure 25. Electrical energy consumed by the heat pump for DHW preparation in January

The number of daily activations of the heat pump is around 2.5. This means that when the heat pump is activated, it is not possible to store enough energy to cover the daily energy demand. This is a problem because such system does not allow to be flexible as every time that there is a withdrawal of domestic hot water it is necessary to turn the heat pump on.

To have a higher flexibility and increase the effectiveness of the advanced control logic it is necessary to increase the size of the thermal energy storage by three times. This allows to have on average only one daily activation. If the activation of the heat pump is defined in a smart way, it is possible to reduce the electrical energy withdrawn from the grid for domestic hot water preparation.

In Figure 26 a comparison on the number of daily activations of the heat pump, for the preparation of domestic hot water, obtained with different combinations of control logics and thermal energy storage volumes. RBC stands for rule-based control, AC for advanced control, TES = 1m^3 for thermal energy storage of 1000 liters and TES = 3m^3 for thermal energy storage of 3000 liters. The results of the four reference months are reported.

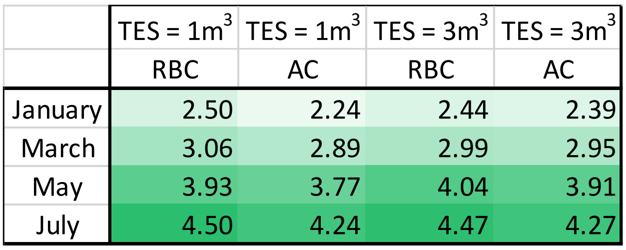


	January				March				May				July			
	TES = 1m^3	TES = 1m^3	TES = 3m^3	TES = 3m^3	TES = 1m^3	TES = 1m^3	TES = 3m^3	TES = 3m^3	TES = 1m^3	TES = 1m^3	TES = 3m^3	TES = 3m^3	TES = 1m^3	TES = 1m^3	TES = 3m^3	TES = 3m^3
	RBC	AC	RBC	AC	RBC	AC	RBC	AC	RBC	AC	RBC	AC	RBC	AC	RBC	AC
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	1	0	0	0	1	0	0	0	3	0	0	0
3	1	0	0	0	2	0	1	0	1	0	0	0	1	0	2	0
4	0	0	0	0	2	0	0	0	0	0	0	0	1	0	0	0
5	2	0	0	0	0	0	0	0	3	0	0	0	1	0	0	0
6	3	1	0	0	0	0	0	0	0	1	0	0	0	1	0	0
7	14	13	8	0	8	5	6	0	5	4	2	1	8	8	2	0
8	6	9	6	1	13	12	9	2	14	17	8	6	13	9	8	6
9	2	2	1	0	2	3	0	1	2	3	1	3	1	4	2	2
10	2	4	3	2	3	3	2	4	3	3	1	4	1	11	1	8
11	3	17	0	7	2	3	2	4	1	0	1	0	2	3	1	2
12	2	7	3	5	2	1	0	3	2	2	0	1	2	0	2	3
13	7	4	2	5	4	9	2	3	0	1	2	0	5	6	3	2
14	4	3	1	1	1	2	1	2	4	3	1	1	2	2	0	1
15	0	0	0	1	2	1	0	2	2	5	1	0	2	1	1	0
16	4	0	2	5	1	4	2	0	1	2	1	1	5	3	1	0
17	6	5	3	1	1	3	2	2	5	1	3	5	4	4	0	0
18	6	2	1	1	7	4	3	3	5	9	1	1	6	5	2	3
19	4	3	1	1	7	7	1	2	4	2	0	2	6	5	2	1
20	2	1	1	1	6	3	1	2	2	7	2	2	5	5	1	1
21	4	5	1	0	6	3	1	1	3	1	1	2	2	2	3	2
22	3	2	2	1	3	2	1	0	6	2	3	1	4	1	1	0
23	1	0	0	1	0	2	0	0	0	1	1	0	1	0	0	0
24	1	1	0	0	2	0	1	0	1	0	0	0	1	0	1	0
TOTAL	77	79	35	33	75	67	35	31	65	64	29	30	76	70	33	31

Figure 26. Number of daily activations of the heat pump for different control strategies and TES volumes (January, March, May and July)

It is interesting to notice that the rule-based control combined with the larger TES can reduce the number of daily activations od the heat pump. However, most of the activations are concentrated between 7AM and 8AM. The advanced control logic is able to shift the load only when the larger thermal energy storage is used. In January the load is delayed by 4 hours. In warmer months this delay is reduced. This is because during summer the PV system produces enough electricity already in the morning and the outdoor temperature are not very low.

Figure 27 reports the monthly average COP of the heat pump for the production of domestic hot water for different combinations of control strategy and TES sizes. The data are reported for the four reference months. The thermal energy produced by the heat pump is similar because the same withdrawal profile was used for the different simulations.

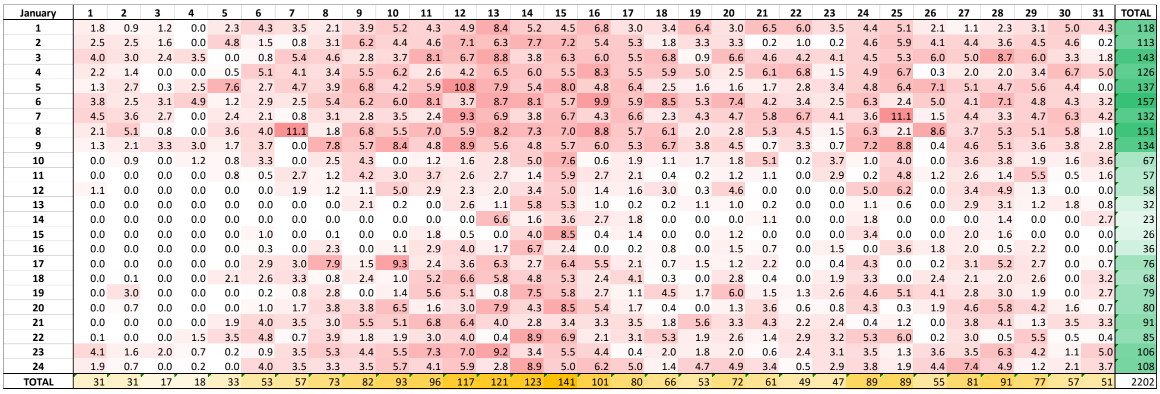


	TES = 1m^3	TES = 1m^3	TES = 3m^3	TES = 3m^3
	RBC	AC	RBC	AC
January	2.50	2.24	2.44	2.39
March	3.06	2.89	2.99	2.95
May	3.93	3.77	4.04	3.91
July	4.50	4.24	4.47	4.27

Figure 27. Monthly average COP of heat pump for DHW preparation for different control strategies and TES volumes (January, March, May and July)

The advanced control logic reduces the COP of the heat pump because it implies a higher setpoint temperature for the heat pump. The loss of performance due to the increase of the temperature at the load side of the heat pump is not recovered by the increase of temperature at the source side. Therefore, the COP decreases. It is however interesting to notice that with the advanced control logic the monthly averaged COP increases for the larger storage. This does not happen for the rule-based control. This fact further demonstrates that in order to use an advanced control logic it is necessary to increase the size of the thermal energy storage to enhance the system flexibility.

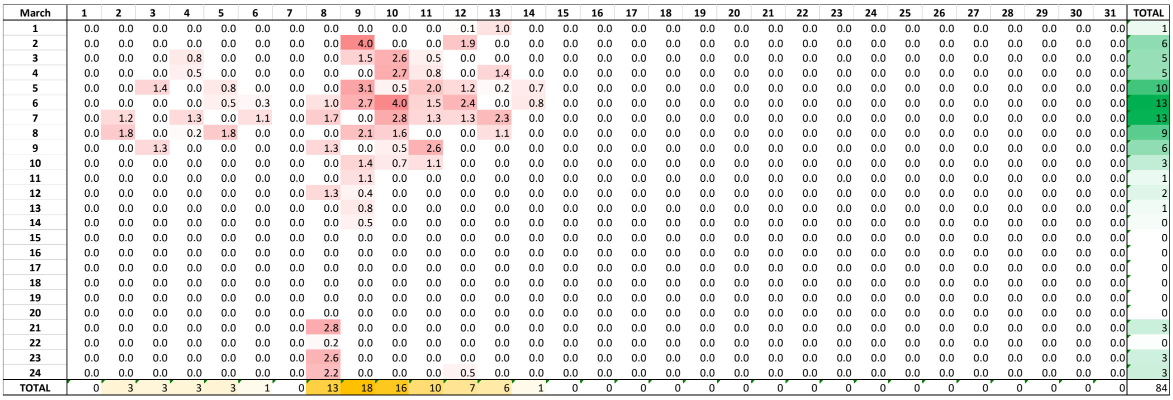
Figure 28 and Figure 29 report the hourly space heating needs of the building in January and March obtained with the rule-based control.



January	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	TOTAL
1	1.8	0.9	1.2	0.0	2.3	4.3	3.5	2.1	3.9	5.2	4.3	4.9	8.4	5.2	4.5	6.8	3.0	3.4	6.4	3.0	6.5	6.0	3.5	4.4	5.1	2.1	1.1	2.3	3.1	5.0	4.3	118
2	2.5	2.5	1.6	0.0	4.8	1.5	0.8	3.1	6.2	4.4	4.6	7.1	6.3	7.7	7.2	5.4	5.3	1.8	3.3	3.3	0.2	1.0	0.2	4.6	5.9	4.1	4.4	3.6	4.5	4.6	0.2	113
3	4.0	3.0	2.4	3.5	0.0	0.8	5.4	4.6	2.8	3.7	8.1	6.7	8.8	3.8	6.3	6.0	5.5	6.8	0.9	6.6	4.6	4.2	4.1	4.5	5.3	6.0	5.0	8.7	6.0	3.3	1.8	143
4	2.2	1.4	0.0	0.0	0.5	5.1	4.1	3.4	5.5	6.2	2.6	4.2	6.5	6.0	5.5	8.3	5.5	5.9	5.0	2.5	6.1	6.8	1.5	4.9	6.7	0.3	2.0	2.0	3.4	6.7	5.0	126
5	1.3	2.7	0.3	2.5	7.6	2.7	4.7	3.9	6.8	4.2	5.9	10.8	7.9	5.4	8.0	4.8	6.4	2.5	1.6	1.6	1.7	2.8	3.4	4.8	6.4	7.1	5.1	4.7	5.6	4.4	0.0	137
6	3.8	2.5	3.1	4.9	1.2	2.9	2.5	5.4	6.2	6.0	8.1	3.7	8.7	8.1	5.7	9.9	5.9	8.5	5.3	7.4	4.2	3.4	2.5	6.3	2.4	5.0	4.1	7.1	4.8	4.3	3.2	157
7	4.5	3.6	2.7	0.0	2.4	2.1	0.8	3.1	2.8	3.5	2.4	9.3	6.9	3.8	6.7	4.3	6.6	2.3	4.3	4.7	5.8	6.7	4.1	3.6	11.1	1.5	4.4	3.3	4.7	6.3	4.2	132
8	2.1	5.1	0.8	0.0	3.6	4.0	11.1	1.8	6.8	5.5	7.0	5.9	8.2	7.3	7.0	8.8	5.7	6.1	2.0	2.8	5.3	4.5	1.5	6.3	2.1	8.6	3.7	5.3	5.1	5.8	1.0	151
9	1.3	2.1	3.3	3.0	1.7	3.7	0.0	7.8	5.7	8.4	4.8	8.9	5.6	4.8	5.7	6.0	5.3	6.7	3.8	4.5	0.7	3.3	0.7	7.2	8.8	0.4	4.6	5.1	3.6	3.8	2.8	134
10	0.0	0.9	0.0	1.2	0.8	3.3	0.0	2.5	4.3	0.0	1.2	1.6	2.8	5.0	7.6	0.6	1.9	1.1	1.7	1.8	5.1	0.2	3.7	1.0	4.0	0.0	3.6	3.8	1.9	1.6	3.6	67
11	0.0	0.0	0.0	0.0	0.8	0.5	2.7	1.2	4.2	3.0	3.7	2.6	2.7	1.4	5.9	2.7	2.1	0.4	0.2	1.2	1.1	0.0	2.9	0.2	4.8	1.2	2.6	1.4	5.5	0.5	1.6	57
12	1.1	0.0	0.0	0.0	0.0	0.0	1.9	1.2	1.1	5.0	2.9	2.3	2.0	3.4	5.0	1.4	1.6	3.0	0.3	4.6	0.0	0.0	0.0	5.0	6.2	0.0	3.4	4.9	1.3	0.0	0.0	58
13	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.1	0.2	0.0	2.6	1.1	5.8	5.3	1.0	0.2	0.2	1.1	1.0	0.2	0.0	0.0	1.1	0.6	0.0	2.9	3.1	1.2	1.8	0.8	32
14	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	6.6	1.6	3.6	2.7	1.8	0.0	0.0	0.0	1.1	0.0	0.0	1.8	0.0	0.0	0.0	1.4	0.0	0.0	2.7	23
15	0.0	0.0	0.0	0.0	0.0	1.0	0.0	0.1	0.0	0.0	1.8	0.5	0.0	4.0	8.5	0.4	1.4	0.0	0.0	1.2	0.0	0.0	0.0	3.4	0.0	0.0	2.0	1.6	0.0	0.0	0.0	26
16	0.0	0.0	0.0	0.0	0.0	0.3	0.0	2.3	0.0	1.1	2.9	4.0	1.7	6.7	2.4	0.0	0.2	0.8	0.0	1.5	0.7	0.0	1.5	0.0	3.6	1.8	2.0	0.5	2.2	0.0	0.0	36
17	0.0	0.0	0.0	0.0	0.0	2.9	3.0	7.9	1.5	9.3	2.4	3.6	6.3	2.7	6.4	5.5	2.1	0.7	1.5	1.2	2.2	0.0	0.4	4.3	0.0	0.2	3.1	5.2	2.7	0.0	0.7	76
18	0.0	0.1	0.0	0.0	2.1	2.6	3.3	0.8	2.4	1.0	5.2	6.6	5.8	4.8	5.3	2.4	4.1	0.3	0.0	2.8	0.4	0.0	1.9	3.3	0.0	2.4	2.1	2.0	2.6	0.0	3.2	68
19	0.0	3.0	0.0	0.0	0.0	0.2	0.8	2.8	0.0	1.4	5.6	5.1	0.8	7.5	5.8	2.7	1.1	4.5	1.7	6.0	1.5	1.3	2.6	4.6	5.1	4.1	2.8	3.0	1.9	0.0	2.7	79
20	0.0	0.7	0.0	0.0	0.0	1.0	1.7	3.8	3.8	6.5	1.6	3.0	7.9	4.3	8.5	5.4	1.7	0.4	0.0	1.3	3.6	0.6	0.8	4.3	0.3	1.9	4.6	5.8	4.2	1.6	0.7	80
21	0.0	0.0	0.0	0.0	1.9	4.0	3.5	3.0	5.5	5.1	6.8	6.4	4.0	2.8	3.4	3.3	3.5	1.8	5.6	3.3	4.3	2.2	2.4	0.4	1.2	0.0	3.8	4.1	1.3	3.5	3.3	91
22	0.1	0.0	0.0	1.5	3.5	4.8	0.7	3.9	1.8	1.9	3.0	4.0	0.4	8.9	6.9	2.1	3.1	5.3	1.9	2.6	1.4	2.9	3.2	5.3	6.0	0.2	3.0	0.5	5.5	0.5	0.4	85
23	4.1	1.6	2.0	0.7	0.2	0.9	3.5	5.3	4.4	5.5	7.3	7.0	9.2	3.4	5.5	4.4	0.4	2.0	1.8	2.0	0.6	2.4	3.1	3.5	1.3	3.6	3.5	6.3	4.2	1.1	5.0	106
24	1.9	0.7	0.0	0.2	0.0	4.0	3.5	3.3	3.5	5.7	4.1	5.9	2.8	8.9	5.0	6.2	5.0	1.4	4.7	4.9	3.4	0.5	2.9	3.8	1.9	4.4	7.4	4.9	1.2	2.1	3.7	108
TOTAL	31	31	17	18	33	53	57	73	82	93	96	117	121	123	141	101	80	66	53	72	61	49	47	89	89	55	81	91	77	57	51	2202

Figure 28. Space heating loads for entire building in January

In January the space heating demand of the building is concentrated in the first and last hours of the day, while the thermal load in the central part of the day is very little. The daily need of the building depends on the external temperature. The space heating need of the building in January is about 2200 kWh.

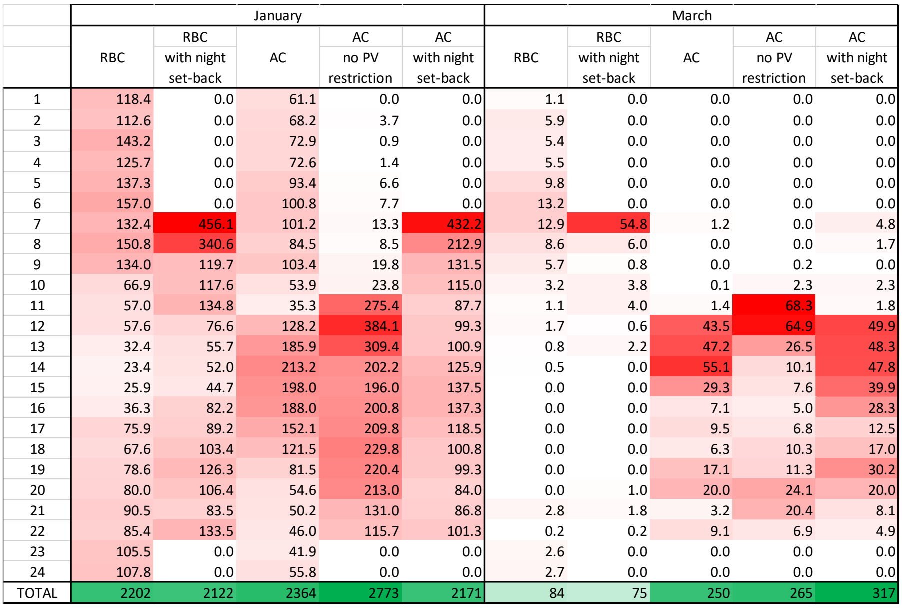


March	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	TOTAL
1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1
2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	4.0	0.0	0.0	1.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	6
3	0.0	0.0	0.0	0.8	0.0	0.0	0.0	0.0	1.5	2.6	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	5
4	0.0	0.0	0.0	0.5	0.0	0.0	0.0	0.0	0.0	2.7	0.8	0.0	1.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	5
5	0.0	0.0	1.4	0.0	0.8	0.0	0.0	0.0	3.1	0.5	2.0	1.2	0.2	0.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	10
6	0.0	0.0	0.0	0.0	0.5	0.3	0.0	1.0	2.7	4.0	1.5	2.4	0.0	0.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	13
7	0.0	1.2	0.0	1.3	0.0	1.1	0.0	1.7	0.0	2.8	1.3	1.3	2.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	13
8	0.0	1.8	0.0	0.2	1.8	0.0	0.0	0.0	2.1	1.6	0.0	0.0	1.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	9
9	0.0	0.0	1.3	0.0	0.0	0.0	0.0	1.3	0.0	0.5	2.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	6
10	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.4	0.7	1.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3
11	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1
12	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.3	0.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2
13	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1
14	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0
15	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0
16	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0
17	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0
18	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0
19	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0
20	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0
21	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3
22	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0
23	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3
24	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.2	0.0	0.0	0.0	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3
TOTAL	0	3	3	3	3	1	0	13	18	16	10	7	6	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	84

Figure 29. Space heating loads for entire building in March

In March the space heating demand is present only for few days and mostly concentrated in the first part of the day. It is possible to notice that starting from mid-March there is no need of space heating. The total space heating need in March is 84 kWh.

Figure 30 reports the space heating needs of the building in January and March with different control strategies. The values represent the monthly thermal energy (kWh) provide to the building in each hour of the day. The control strategy RBC is the simple rule-based control and RBC with night set-back is the rule-based control where the space heating setpoint is lowered by 2 K between 10 PM and 6 AM. AC stands for the advanced control strategy, AC no PV restriction means that the load predictor is not used and the setpoint is shifted in any case, while AC with night set-back is the advanced control where the space heating setpoint is lowered by 2 K between 10 PM and 6 AM.

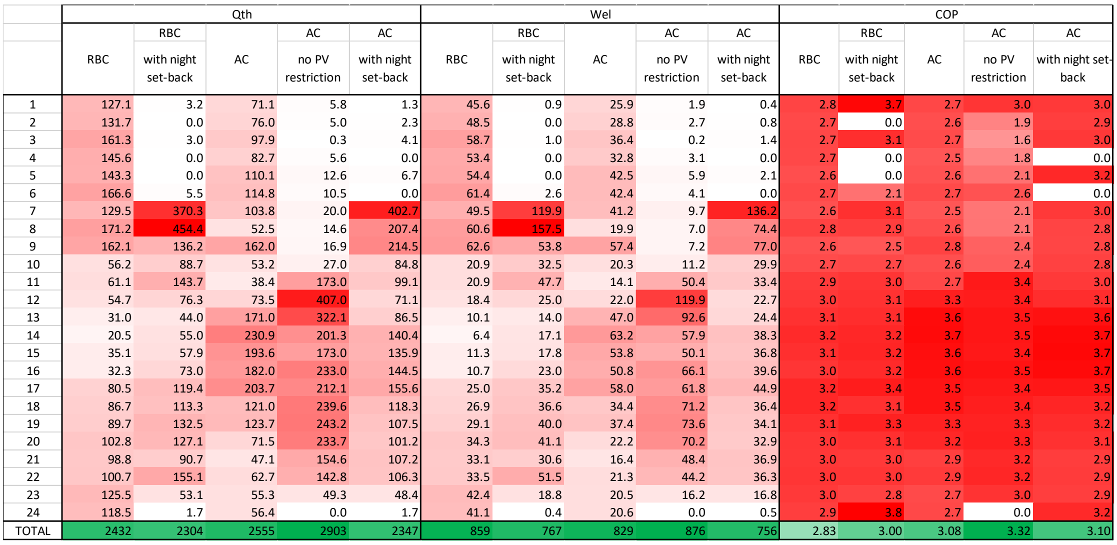


	January					March				
	RBC	RBC with night set-back	AC	AC no PV restriction	AC with night set-back	RBC	RBC with night set-back	AC	AC no PV restriction	AC with night set-back
1	118.4	0.0	61.1	0.0	0.0	1.1	0.0	0.0	0.0	0.0
2	112.6	0.0	68.2	3.7	0.0	5.9	0.0	0.0	0.0	0.0
3	143.2	0.0	72.9	0.9	0.0	5.4	0.0	0.0	0.0	0.0
4	125.7	0.0	72.6	1.4	0.0	5.5	0.0	0.0	0.0	0.0
5	137.3	0.0	93.4	6.6	0.0	9.8	0.0	0.0	0.0	0.0
6	157.0	0.0	100.8	7.7	0.0	13.2	0.0	0.0	0.0	0.0
7	132.4	456.1	101.2	13.3	432.2	12.9	54.8	1.2	0.0	4.8
8	150.8	340.6	84.5	8.5	212.9	8.6	6.0	0.0	0.0	1.7
9	134.0	119.7	103.4	19.8	131.5	5.7	0.8	0.0	0.2	0.0
10	66.9	117.6	53.9	23.8	115.0	3.2	3.8	0.1	2.3	2.3
11	57.0	134.8	35.3	275.4	87.7	1.1	4.0	1.4	68.3	1.8
12	57.6	76.6	128.2	384.1	99.3	1.7	0.6	43.5	64.9	49.9
13	32.4	55.7	185.9	309.4	100.9	0.8	2.2	47.2	26.5	48.3
14	23.4	52.0	213.2	202.2	125.9	0.5	0.0	55.1	10.1	47.8
15	25.9	44.7	198.0	196.0	137.5	0.0	0.0	29.3	7.6	39.9
16	36.3	82.2	188.0	200.8	137.3	0.0	0.0	7.1	5.0	28.3
17	75.9	89.2	152.1	209.8	118.5	0.0	0.0	9.5	6.8	12.5
18	67.6	103.4	121.5	229.8	100.8	0.0	0.0	6.3	10.3	17.0
19	78.6	126.3	81.5	220.4	99.3	0.0	0.0	17.1	11.3	30.2
20	80.0	106.4	54.6	213.0	84.0	0.0	1.0	20.0	24.1	20.0
21	90.5	83.5	50.2	131.0	86.8	2.8	1.8	3.2	20.4	8.1
22	85.4	133.5	46.0	115.7	101.3	0.2	0.2	9.1	6.9	4.9
23	105.5	0.0	41.9	0.0	0.0	2.6	0.0	0.0	0.0	0.0
24	107.8	0.0	55.8	0.0	0.0	2.7	0.0	0.0	0.0	0.0
TOTAL	2202	2122	2364	2773	2171	84	75	250	265	317

Figure 30. Space heating needs of the building in January and March with different control strategies

The advanced control strategy increases the thermal energy provided to the building because of the higher space heating setpoint. The night setbacks are handful to minimize the thermal load during night, but in this way the load is concentrated between 7AM and 8AM. If the advanced control strategy is used without the load prediction, the thermal energy provided to the user is higher.

In January there is not a big difference in terms of energy provided to the building between the rule-based control and the advanced control. The main difference is when this load is given to the building. This shift influences the behavior of the heat pump. In Figure 31 the monthly thermal energy generated (Qth), the electrical energy consumption (Wel) and the COP of the heat pump in space heating mode in January are reported. The values represent the monthly sum subdivided for each hour of the day.

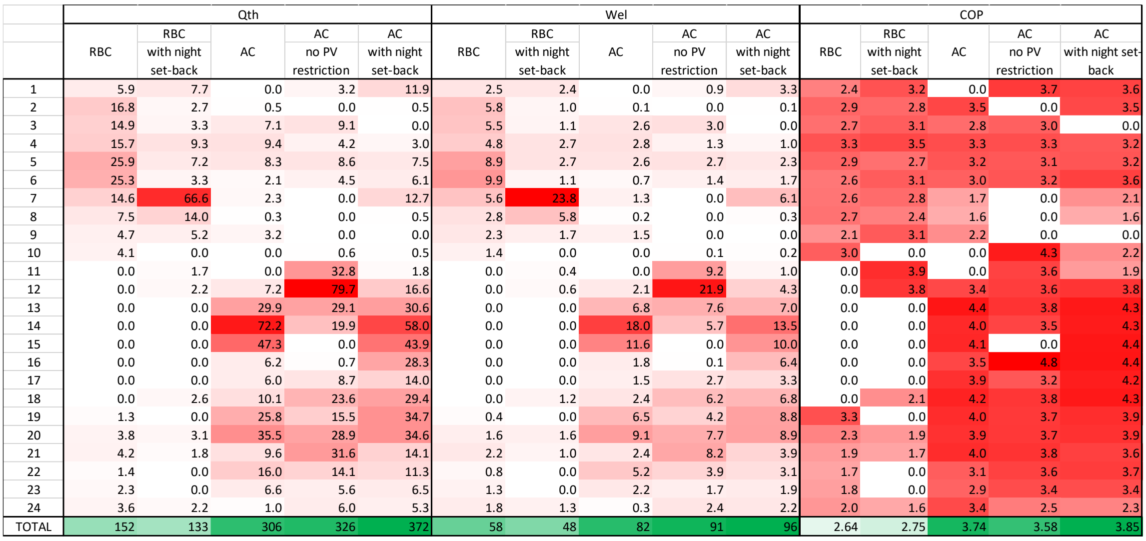


	Qth					Wel					COP				
		RBC		AC	AC		RBC		AC	AC		RBC		AC	AC
	RBC	with night set-back	AC	no PV restriction	with night set-back	RBC	with night set-back	AC	no PV restriction	with night set-back	RBC	with night set-back	AC	no PV restriction	with night set-back
1	127.1	3.2	71.1	5.8	1.3	45.6	0.9	25.9	1.9	0.4	2.8	3.7	2.7	3.0	3.0
2	131.7	0.0	76.0	5.0	2.3	48.5	0.0	28.8	2.7	0.8	2.7	0.0	2.6	1.9	2.9
3	161.3	3.0	97.9	0.3	4.1	58.7	1.0	36.4	0.2	1.4	2.7	3.1	2.7	1.6	3.0
4	145.6	0.0	82.7	5.6	0.0	53.4	0.0	32.8	3.1	0.0	2.7	0.0	2.5	1.8	0.0
5	143.3	0.0	110.1	12.6	6.7	54.4	0.0	42.5	5.9	2.1	2.6	0.0	2.6	2.1	3.2
6	166.6	5.5	114.8	10.5	0.0	61.4	2.6	42.4	4.1	0.0	2.7	2.1	2.7	2.6	0.0
7	129.5	370.3	103.8	20.0	402.7	49.5	119.9	41.2	9.7	136.2	2.6	3.1	2.5	2.1	3.0
8	171.2	454.4	52.5	14.6	207.4	60.6	157.5	19.9	7.0	74.4	2.8	2.9	2.6	2.1	2.8
9	162.1	136.2	162.0	16.9	214.5	62.6	53.8	57.4	7.2	77.0	2.6	2.5	2.8	2.4	2.8
10	56.2	88.7	53.2	27.0	84.8	20.9	32.5	20.3	11.2	29.9	2.7	2.7	2.6	2.4	2.8
11	61.1	143.7	38.4	173.0	99.1	20.9	47.7	14.1	50.4	33.4	2.9	3.0	2.7	3.4	3.0
12	54.7	76.3	73.5	407.0	71.1	18.4	25.0	22.0	119.9	22.7	3.0	3.1	3.3	3.4	3.1
13	31.0	44.0	171.0	322.1	86.5	10.1	14.0	47.0	92.6	24.4	3.1	3.1	3.6	3.5	3.6
14	20.5	55.0	230.9	201.3	140.4	6.4	17.1	63.2	57.9	38.3	3.2	3.2	3.7	3.5	3.7
15	35.1	57.9	193.6	173.0	135.9	11.3	17.8	53.8	50.1	36.8	3.1	3.2	3.6	3.4	3.7
16	32.3	73.0	182.0	233.0	144.5	10.7	23.0	50.8	66.1	39.6	3.0	3.2	3.6	3.5	3.7
17	80.5	119.4	203.7	212.1	155.6	25.0	35.2	58.0	61.8	44.9	3.2	3.4	3.5	3.4	3.5
18	86.7	113.3	121.0	239.6	118.3	26.9	36.6	34.4	71.2	36.4	3.2	3.1	3.5	3.4	3.2
19	89.7	132.5	123.7	243.2	107.5	29.1	40.0	37.4	73.6	34.1	3.1	3.3	3.3	3.3	3.2
20	102.8	127.1	71.5	233.7	101.2	34.3	41.1	22.2	70.2	32.9	3.0	3.1	3.2	3.3	3.1
21	98.8	90.7	47.1	154.6	107.2	33.1	30.6	16.4	48.4	36.9	3.0	3.0	2.9	3.2	2.9
22	100.7	155.1	62.7	142.8	106.3	33.5	51.5	21.3	44.2	36.3	3.0	3.0	2.9	3.2	2.9
23	125.5	53.1	55.3	49.3	48.4	42.4	18.8	20.5	16.2	16.8	3.0	2.8	2.7	3.0	2.9
24	118.5	1.7	56.4	0.0	1.7	41.1	0.4	20.6	0.0	0.5	2.9	3.8	2.7	0.0	3.2
TOTAL	2432	2304	2555	2903	2347	859	767	829	876	756	2.83	3.00	3.08	3.32	3.10

Figure 31. Thermal energy generated by the heat pump, electrical energy consumption of the heat pump and COP in January for different control strategies

The thermal energy generated by the heat pump follows the same profile as the thermal energy provided to the building because the buffer tank has a negligible thermal capacity. The thermal energy produced by the heat pump is higher than the energy given to the building due to the thermal losses in the distribution circuit. The COP of the heat pump is higher during the central part of the day because the outdoor temperature is higher and the distribution temperature is lower. In fact, the control strategy that present the highest COP is the one in which setpoint is always increased during the day. However, because the thermal energy is higher also the electrical consumption is higher than the one obtained with the rule-based control. In January the production of the PV system is low, thus, it is not possible to cover the entire additional load. The advanced control strategy produces higher COP than the rule based control strategy. As a consequence, even if the produced thermal energy is higher, the electrical energy consumption of the heat pump is lower.

In March the advanced control strategy triples the thermal energy provided to the building if compared to the rule-based control. In Figure 32 the monthly thermal energy generated (Qth), the electrical energy consumption (Wel) and the COP of the heat pump in space heating mode in March are reported.



	Qth					Wel					COP				
	RBC	RBC with night set-back	AC	AC no PV restriction	AC with night set-back	RBC	RBC with night set-back	AC	AC no PV restriction	AC with night set-back	RBC	RBC with night set-back	AC	AC no PV restriction	AC with night set-back
1	5.9	7.7	0.0	3.2	11.9	2.5	2.4	0.0	0.9	3.3	2.4	3.2	0.0	3.7	3.6
2	16.8	2.7	0.5	0.0	0.5	5.8	1.0	0.1	0.0	0.1	2.9	2.8	3.5	0.0	3.5
3	14.9	3.3	7.1	9.1	0.0	5.5	1.1	2.6	3.0	0.0	2.7	3.1	2.8	3.0	0.0
4	15.7	9.3	9.4	4.2	3.0	4.8	2.7	2.8	1.3	1.0	3.3	3.5	3.3	3.3	3.2
5	25.9	7.2	8.3	8.6	7.5	8.9	2.7	2.6	2.7	2.3	2.9	2.7	3.2	3.1	3.2
6	25.3	3.3	2.1	4.5	6.1	9.9	1.1	0.7	1.4	1.7	2.6	3.1	3.0	3.2	3.6
7	14.6	66.6	2.3	0.0	12.7	5.6	23.8	1.3	0.0	6.1	2.6	2.8	1.7	0.0	2.1
8	7.5	14.0	0.3	0.0	0.5	2.8	5.8	0.2	0.0	0.3	2.7	2.4	1.6	0.0	1.6
9	4.7	5.2	3.2	0.0	0.0	2.3	1.7	1.5	0.0	0.0	2.1	3.1	2.2	0.0	0.0
10	4.1	0.0	0.0	0.6	0.5	1.4	0.0	0.0	0.1	0.2	3.0	0.0	0.0	4.3	2.2
11	0.0	1.7	0.0	32.8	1.8	0.0	0.4	0.0	9.2	1.0	0.0	3.9	0.0	3.6	1.9
12	0.0	2.2	7.2	79.7	16.6	0.0	0.6	2.1	21.9	4.3	0.0	3.8	3.4	3.6	3.8
13	0.0	0.0	29.9	29.1	30.6	0.0	0.0	6.8	7.6	7.0	0.0	0.0	4.4	3.8	4.3
14	0.0	0.0	72.2	19.9	58.0	0.0	0.0	18.0	5.7	13.5	0.0	0.0	4.0	3.5	4.3
15	0.0	0.0	47.3	0.0	43.9	0.0	0.0	11.6	0.0	10.0	0.0	0.0	4.1	0.0	4.4
16	0.0	0.0	6.2	0.7	28.3	0.0	0.0	1.8	0.1	6.4	0.0	0.0	3.5	4.8	4.4
17	0.0	0.0	6.0	8.7	14.0	0.0	0.0	1.5	2.7	3.3	0.0	0.0	3.9	3.2	4.2
18	0.0	2.6	10.1	23.6	29.4	0.0	1.2	2.4	6.2	6.8	0.0	2.1	4.2	3.8	4.3
19	1.3	0.0	25.8	15.5	34.7	0.4	0.0	6.5	4.2	8.8	3.3	0.0	4.0	3.7	3.9
20	3.8	3.1	35.5	28.9	34.6	1.6	1.6	9.1	7.7	8.9	2.3	1.9	3.9	3.7	3.9
21	4.2	1.8	9.6	31.6	14.1	2.2	1.0	2.4	8.2	3.9	1.9	1.7	4.0	3.8	3.6
22	1.4	0.0	16.0	14.1	11.3	0.8	0.0	5.2	3.9	3.1	1.7	0.0	3.1	3.6	3.7
23	2.3	0.0	6.6	5.6	6.5	1.3	0.0	2.2	1.7	1.9	1.8	0.0	2.9	3.4	3.4
24	3.6	2.2	1.0	6.0	5.3	1.8	1.3	0.3	2.4	2.2	2.0	1.6	3.4	2.5	2.3
TOTAL	152	133	306	326	372	58	48	82	91	96	2.64	2.75	3.74	3.58	3.85

Figure 32. Thermal energy generated by the heat pump, electrical energy consumption of the heat pump and COP in March for different control strategies

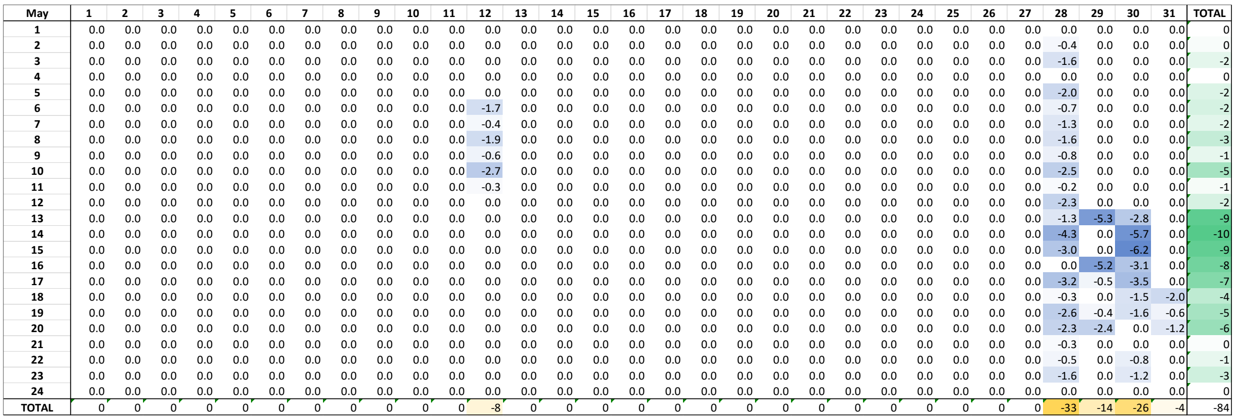
Like in January, the thermal energy generated by the heat pump follows the same profile as the thermal energy provided to the building. The thermal energy produced by the heat pump is higher than the energy given to the building due to the thermal losses in the distribution circuit. The advanced control strategy results in higher COP if compared to the rule-based control. However, because the thermal energy is three times higher, the electrical consumption is anyway higher than the one obtained with the rule-based control. In March the production of the PV system is higher than in January and the thermal needs of the building are lower, thus, it is possible to cover the entire additional load. The adaption of the advanced control strategy does not increase the electrical energy withdrawn from the grid. In order to limit the increase of the electrical consumption it is possible to increase the space heating setpoint by 1 K instead of 2 K during the mild heating season.

The COP of the heat pump in space heating mode is higher in the central part of the day because the temperature at the evaporator is higher and, due to the climatic curve, the setpoint of the heat pump is lower. The advanced control strategy for space heating proved to be able to shift the load in toward the central part of the day without significantly increasing the electrical consumption of the heat pump. The night setbacks are useful to avoid the activation of the heat pump during the night, but they are not very effective in reducing the thermal load nor in shifting the load toward the central part of the day.

During the cold heating season (January) the building demand is high. Even if the advanced control logic increases the thermal load, because of the higher COP, the electrical consumption is more or less the same. Nevertheless, in the central part of the day the load might be covered with the PV. To reduce the electricity withdrawn from the grid it is necessary to change the space heating setpoint only in the days in which the PV system is able to cover at least half of the total predicted consumption.

During the mild heating season (March) the building demand is low. In this case, the advanced control logic increases the electrical consumption. However, this higher electrical energy consumption is concentrated in the central part of the day and can be covered by PV system production. If the increase of the setpoint to 1 K during the mild seasons it is possible to further reduce the electrical consumption of the heat pump.

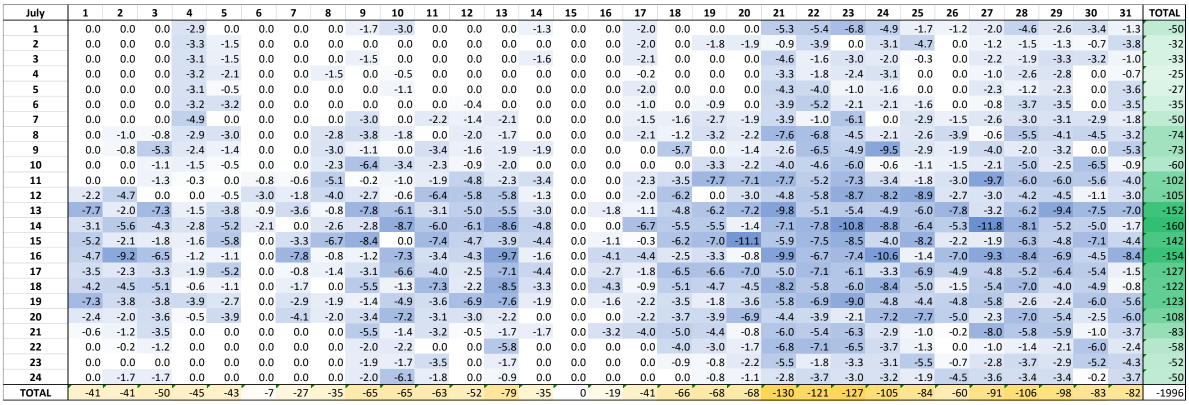
Figure 33 and Figure 34 report the hourly space cooling needs of the building in May and July obtained with the rule-based control.



May	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	TOTAL
1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0
2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.4	0.0	0.0	0.0	0
3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-1.6	0.0	0.0	0.0	-2
4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0
5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-2.0	0.0	0.0	0.0	-2
6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-1.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.7	0.0	0.0	0.0	-2
7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-1.3	0.0	0.0	0.0	-2
8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-1.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-1.6	0.0	0.0	0.0	-3
9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.8	0.0	0.0	0.0	-1
10	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-2.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-2.5	0.0	0.0	0.0	-5
11	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.2	0.0	0.0	0.0	-1
12	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-2.3	0.0	0.0	0.0	-2
13	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-1.3	-5.3	-2.8	0.0	-9
14	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-4.3	0.0	-5.7	0.0	-10
15	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-3.0	0.0	-6.2	0.0	-9
16	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-5.2	-3.1	0.0	-8
17	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-3.2	-0.5	-3.5	0.0	-7
18	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.3	0.0	-1.5	-2.0	-4
19	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-2.6	-0.4	-1.6	-0.6	-5
20	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-2.3	-2.4	0.0	-1.2	-6
21	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.3	0.0	0.0	0.0	0
22	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-0.5	0.0	-0.8	0.0	-1
23	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-1.6	0.0	-1.2	0.0	-3
24	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0
TOTAL	0	0	0	0	0	0	0	0	0	0	0	-8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-33	-14	-26	-4	-84

Figure 33. Space cooling loads for entire building in May

The space cooling demand of the building in May is concentrated in few days. Generally, the demand is concentrated in the afternoon. The daily need of the building depends on the external temperature and the solar irradiance. The space cooling need of the building in May is quite low (84 kWh).

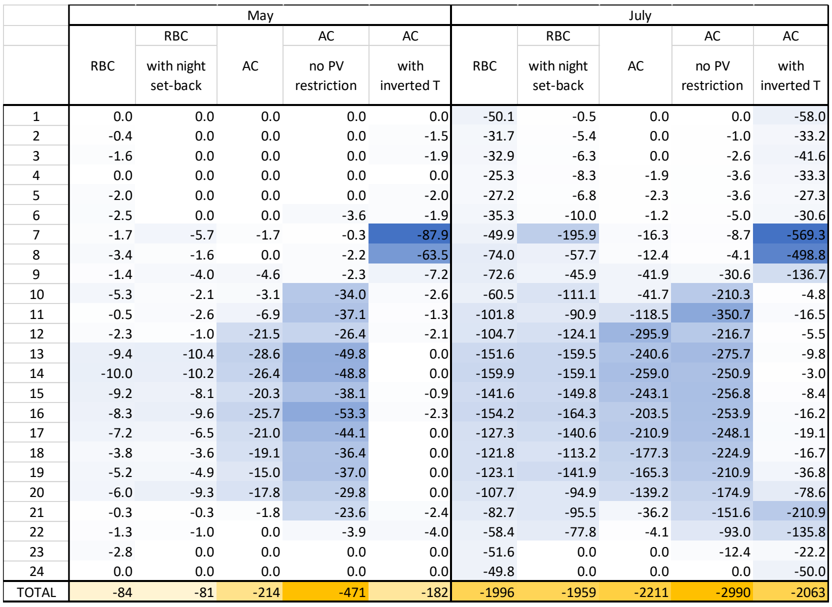


July	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	TOTAL
1	0.0	0.0	0.0	-2.9	0.0	0.0	0.0	0.0	-1.7	-3.0	0.0	0.0	0.0	-1.3	0.0	0.0	-2.0	0.0	0.0	0.0	-5.3	-5.4	-6.8	-4.9	-1.7	-1.2	-2.0	-4.6	-2.6	-3.4	-1.3	-50
2	0.0	0.0	0.0	-3.3	-1.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-2.0	0.0	-1.8	-1.9	-0.9	-3.9	0.0	-3.1	-4.7	0.0	-1.2	-1.5	-1.3	-0.7	-3.8	-32
3	0.0	0.0	0.0	-3.1	-1.5	0.0	0.0	0.0	-1.5	0.0	0.0	0.0	0.0	-1.6	0.0	0.0	-2.1	0.0	0.0	0.0	-4.6	-1.6	-3.0	-2.0	-0.3	0.0	-2.2	-1.9	-3.3	-3.2	-1.0	-33
4	0.0	0.0	0.0	-3.2	-2.1	0.0	0.0	-1.5	0.0	-0.5	0.0	0.0	0.0	0.0	0.0	0.0	-0.2	0.0	0.0	0.0	-3.3	-1.8	-2.4	-3.1	0.0	0.0	-1.0	-2.6	-2.8	0.0	-0.7	-25
5	0.0	0.0	0.0	-3.1	-0.5	0.0	0.0	0.0	0.0	-1.1	0.0	0.0	0.0	0.0	0.0	0.0	-2.0	0.0	0.0	0.0	-4.3	-4.0	-1.0	-1.6	0.0	0.0	-2.3	-1.2	-2.3	0.0	-3.6	-27
6	0.0	0.0	0.0	-3.2	-3.2	0.0	0.0	0.0	0.0	0.0	0.0	-0.4	0.0	0.0	0.0	0.0	-1.0	0.0	-0.9	0.0	-3.9	-5.2	-2.1	-2.1	-1.6	0.0	-0.8	-3.7	-3.5	0.0	-3.5	-35
7	0.0	0.0	0.0	-4.9	0.0	0.0	0.0	0.0	-3.0	0.0	-2.2	-1.4	-2.1	0.0	0.0	0.0	-1.5	-1.6	-2.7	-1.9	-3.9	-1.0	-6.1	0.0	-2.9	-1.5	-2.6	-3.0	-3.1	-2.9	-1.8	-50
8	0.0	-1.0	-0.8	-2.9	-3.0	0.0	0.0	-2.8	-3.8	-1.8	0.0	-2.0	-1.7	0.0	0.0	0.0	-2.1	-1.2	-3.2	-2.2	-7.6	-6.8	-4.5	-2.1	-2.6	-3.9	-0.6	-5.5	-4.1	-4.5	-3.2	-74
9	0.0	-0.8	-5.3	-2.4	-1.4	0.0	0.0	-3.0	-1.1	0.0	-3.4	-1.6	-1.9	-1.9	0.0	0.0	0.0	-5.7	0.0	-1.4	-2.6	-6.5	-4.9	-9.5	-2.9	-1.9	-4.0	-2.0	-3.2	0.0	-5.3	-73
10	0.0	0.0	-1.1	-1.5	-0.5	0.0	0.0	-2.3	-6.4	-3.4	-2.3	-0.9	-2.0	0.0	0.0	0.0	0.0	0.0	-3.3	-2.2	-4.0	-4.6	-6.0	-0.6	-1.1	-1.5	-2.1	-5.0	-2.5	-6.5	-0.9	-60
11	0.0	0.0	-1.3	-0.3	0.0	-0.8	-0.6	-5.1	-0.2	-1.0	-1.9	-4.8	-2.3	-3.4	0.0	0.0	-2.3	-3.5	-7.7	-7.1	-7.7	-5.2	-7.3	-3.4	-1.8	-3.0	-9.7	-6.0	-6.0	-5.6	-4.0	-102
12	-2.2	-4.7	0.0	0.0	-0.5	-3.0	-1.8	-4.0	-2.7	-0.6	-6.4	-5.8	-5.8	-1.3	0.0	0.0	-2.0	-6.2	0.0	-3.0	-4.8	-5.8	-8.7	-8.2	-8.9	-2.7	-3.0	-4.2	-4.5	-1.1	-3.0	-105
13	-7.7	-2.0	-7.3	-1.5	-3.8	-0.9	-3.6	-0.8	-7.8	-6.1	-3.1	-5.0	-5.5	-3.0	0.0	-1.8	-1.1	-4.8	-6.2	-7.2	-9.8	-5.1	-5.4	-4.9	-6.0	-7.8	-3.2	-6.2	-9.4	-7.5	-7.0	-152
14	-3.1	-5.6	-4.3	-2.8	-5.2	-2.1	0.0	-2.6	-2.8	-8.7	-6.0	-6.1	-8.6	-4.8	0.0	0.0	-6.7	-5.5	-5.5	-1.4	-7.1	-7.8	-10.8	-8.8	-6.4	-5.3	-11.8	-8.1	-5.2	-5.0	-1.7	-160
15	-5.2	-2.1	-1.8	-1.6	-5.8	0.0	-3.3	-6.7	-8.4	0.0	-7.4	-4.7	-3.9	-4.4	0.0	-1.1	-0.3	-6.2	-7.0	-11.1	-5.9	-7.5	-8.5	-4.0	-8.2	-2.2	-1.9	-6.3	-4.8	-7.1	-4.4	-142
16	-4.7	-9.2	-6.5	-1.2	-1.1	0.0	-7.8	-0.8	-1.2	-7.3	-3.4	-4.3	-9.7	-1.6	0.0	-4.1	-4.4	-2.5	-3.3	-0.8	-9.9	-6.7	-7.4	-10.6	-1.4	-7.0	-9.3	-8.4	-6.9	-4.5	-8.4	-154
17	-3.5	-2.3	-3.3	-1.9	-5.2	0.0	-0.8	-1.4	-3.1	-6.6	-4.0	-2.5	-7.1	-4.4	0.0	-2.7	-1.8	-6.5	-6.6	-7.0	-5.0	-7.1	-6.1	-3.3	-6.9	-4.9	-4.8	-5.2	-6.4	-5.4	-1.5	-127
18	-4.2	-4.5	-5.1	-0.6	-1.1	0.0	-1.7	0.0	-5.5	-1.3	-7.3	-2.2	-8.5	-3.3	0.0	-4.3	-0.9	-5.1	-4.7	-4.5	-8.2	-5.8	-6.0	-8.4	-5.0	-1.5	-5.4	-7.0	-4.0	-4.9	-0.8	-122
19	-7.3	-3.8	-3.8	-3.9	-2.7	0.0	-2.9	-1.9	-1.4	-4.9	-3.6	-6.9	-7.6	-1.9	0.0	-1.6	-2.2	-3.5	-1.8	-3.6	-5.8	-6.9	-9.0	-4.8	-4.4	-4.8	-5.8	-2.6	-2.4	-6.0	-5.6	-123
20	-2.4	-2.0	-3.6	-0.5	-3.9	0.0	-4.1	-2.0	-3.4	-7.2	-3.1	-3.0	-2.2	0.0	0.0	0.0	-2.2	-3.7	-3.9	-6.9	-4.4	-3.9	-2.1	-7.2	-7.7	-5.0	-2.3	-7.0	-5.4	-2.5	-6.0	-108
21	-0.6	-1.2	-3.5	0.0	0.0	0.0	0.0	0.0	-5.5	-1.4	-3.2	-0.5	-1.7	-1.7	0.0	-3.2	-4.0	-5.0	-4.4	-0.8	-6.0	-5.4	-6.3	-2.9	-1.0	-0.2	-8.0	-5.8	-5.9	-1.0	-3.7	-83
22	0.0	-0.2	-1.2	0.0	0.0	0.0	0.0	0.0	-2.0	-2.2	0.0	0.0	-5.8	0.0	0.0	0.0	0.0	-4.0	-3.0	-1.7	-6.8	-7.1	-6.5	-3.7	-1.3	0.0	-1.0	-1.4	-2.1	-6.0	-2.4	-58
23	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-1.9	-1.7	-3.5	0.0	-1.7	0.0	0.0	0.0	0.0	-0.9	-0.8	-2.2	-5.5	-1.8	-3.3	-3.1	-5.5	-0.7	-2.8	-3.7	-2.9	-5.2	-4.3	-52
24	0.0	-1.7	-1.7	0.0	0.0	0.0	0.0	0.0	-2.0	-6.1	-1.8	0.0	-0.9	0.0	0.0	0.0	0.0	0.0	-0.8	-1.1	-2.8	-3.7	-3.0	-3.2	-1.9	-4.5	-3.6	-3.4	-3.4	-0.2	-3.7	-50
TOTAL	-41	-41	-50	-45	-43	-7	-27	-35	-65	-65	-63	-52	-79	-35	0	-19	-41	-66	-68	-68	-130	-121	-127	-105	-84	-60	-91	-106	-98	-83	-82	-1996

Figure 34. Space cooling loads for entire building in July

In July, the space cooling demand is spread throughout the entire month except for few days. The load is higher during the afternoon hours. The space cooling need of the building in July is about 2000 kWh.

Figure 35 reports the space cooling needs of the building in May and July with different control strategies. The values represent the monthly thermal energy (kWh) provide to the building in each hour of the day. The control strategy RBC is the simple rule-based control and RBC with night set-back is the rule-based control where the space heating setpoint is increased by 2 K between 10 PM and 6 AM. AC stands for the advanced control strategy, AC no PV restriction means that the load predictor is not used and the setpoint is shifted in any case, while AC with inverted T is the advanced control where the space cooling setpoint is lowered by 2 K when the outdoor temperature is lower than the predicted daily average temperature.

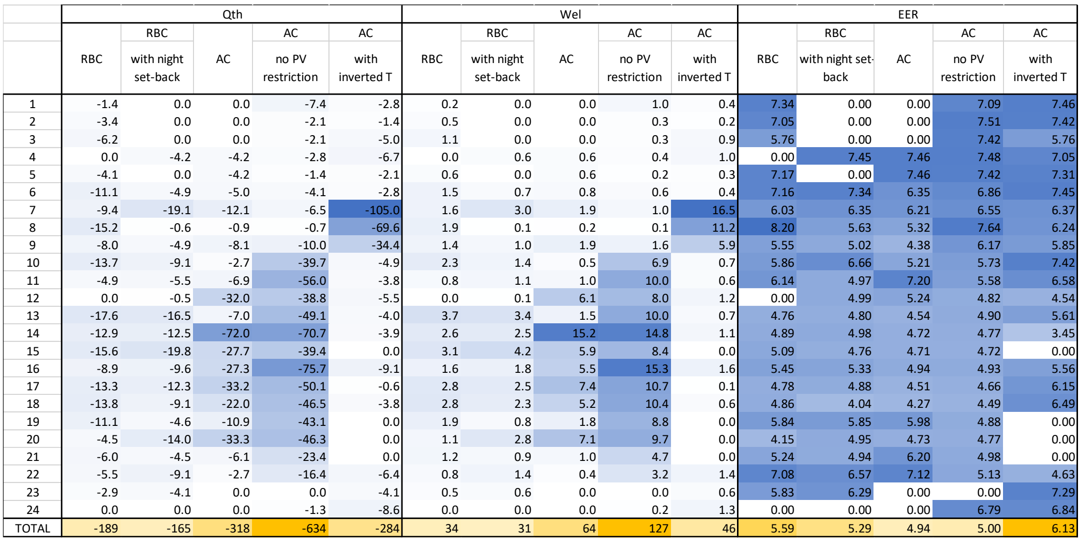


	May					July				
		RBC		AC	AC		RBC		AC	AC
	RBC	with night set-back	AC	no PV restriction	with inverted T	RBC	with night set-back	AC	no PV restriction	with inverted T
1	0.0	0.0	0.0	0.0	0.0	-50.1	-0.5	0.0	0.0	-58.0
2	-0.4	0.0	0.0	0.0	-1.5	-31.7	-5.4	0.0	-1.0	-33.2
3	-1.6	0.0	0.0	0.0	-1.9	-32.9	-6.3	0.0	-2.6	-41.6
4	0.0	0.0	0.0	0.0	0.0	-25.3	-8.3	-1.9	-3.6	-33.3
5	-2.0	0.0	0.0	0.0	-2.0	-27.2	-6.8	-2.3	-3.6	-27.3
6	-2.5	0.0	0.0	-3.6	-1.9	-35.3	-10.0	-1.2	-5.0	-30.6
7	-1.7	-5.7	-1.7	-0.3	-87.9	-49.9	-195.9	-16.3	-8.7	-569.3
8	-3.4	-1.6	0.0	-2.2	-63.5	-74.0	-57.7	-12.4	-4.1	-498.8
9	-1.4	-4.0	-4.6	-2.3	-7.2	-72.6	-45.9	-41.9	-30.6	-136.7
10	-5.3	-2.1	-3.1	-34.0	-2.6	-60.5	-111.1	-41.7	-210.3	-4.8
11	-0.5	-2.6	-6.9	-37.1	-1.3	-101.8	-90.9	-118.5	-350.7	-16.5
12	-2.3	-1.0	-21.5	-26.4	-2.1	-104.7	-124.1	-295.9	-216.7	-5.5
13	-9.4	-10.4	-28.6	-49.8	0.0	-151.6	-159.5	-240.6	-275.7	-9.8
14	-10.0	-10.2	-26.4	-48.8	0.0	-159.9	-159.1	-259.0	-250.9	-3.0
15	-9.2	-8.1	-20.3	-38.1	-0.9	-141.6	-149.8	-243.1	-256.8	-8.4
16	-8.3	-9.6	-25.7	-53.3	-2.3	-154.2	-164.3	-203.5	-253.9	-16.2
17	-7.2	-6.5	-21.0	-44.1	0.0	-127.3	-140.6	-210.9	-248.1	-19.1
18	-3.8	-3.6	-19.1	-36.4	0.0	-121.8	-113.2	-177.3	-224.9	-16.7
19	-5.2	-4.9	-15.0	-37.0	0.0	-123.1	-141.9	-165.3	-210.9	-36.8
20	-6.0	-9.3	-17.8	-29.8	0.0	-107.7	-94.9	-139.2	-174.9	-78.6
21	-0.3	-0.3	-1.8	-23.6	-2.4	-82.7	-95.5	-36.2	-151.6	-210.9
22	-1.3	-1.0	0.0	-3.9	-4.0	-58.4	-77.8	-4.1	-93.0	-135.8
23	-2.8	0.0	0.0	0.0	0.0	-51.6	0.0	0.0	-12.4	-22.2
24	0.0	0.0	0.0	0.0	0.0	-49.8	0.0	0.0	0.0	-50.0
TOTAL	-84	-81	-214	-471	-182	-1996	-1959	-2211	-2990	-2063

Figure 35. Space cooling needs of the building in May and July with different control strategies

The advanced control strategy increases the thermal energy provided to the building because of the lower space cooling setpoint without shifting much of the load. The night setbacks have a little impact on the behavior of the system because the space cooling demand is already small during night. If the advanced control strategy is used without the load prediction, the thermal energy provided to the user is much higher. If the control logic is activated with the inverted temperature the load is shifted toward the morning and evening hours.

In May the advanced control strategy increases the thermal energy provided to the building by two or three times if compared to the rule-based control. In Figure 36 the monthly thermal energy generated (Qth), the electrical energy consumption (Wel) and the energy efficiency ratio (EER) of the heat pump in space cooling mode in May are reported.

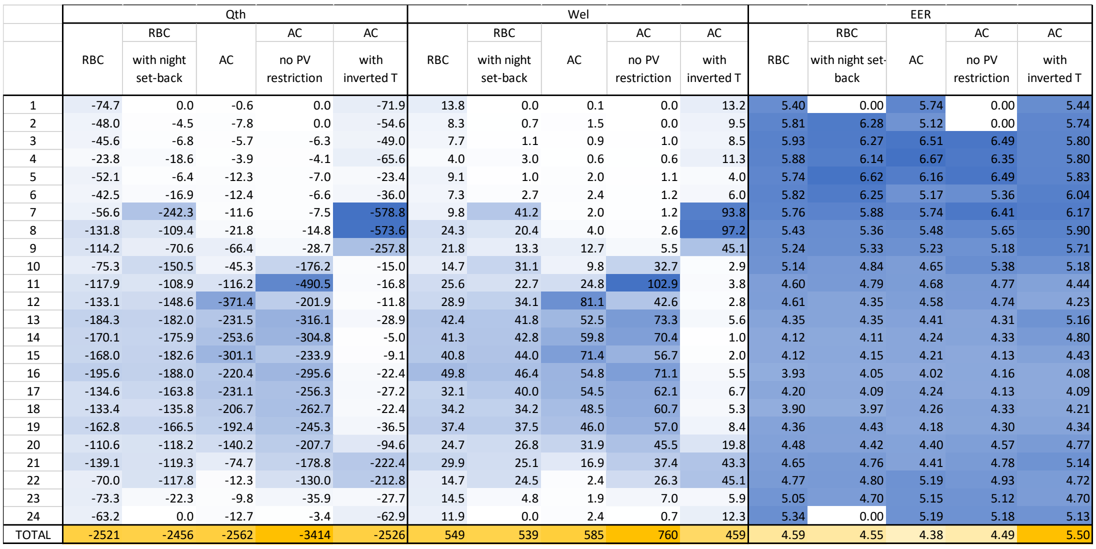


	Qth					Wel					EER				
		RBC		AC	AC		RBC		AC	AC		RBC		AC	AC
	RBC	with night set-back	AC	no PV restriction	with inverted T	RBC	with night set-back	AC	no PV restriction	with inverted T	RBC	with night set-back	AC	no PV restriction	with inverted T
1	-1.4	0.0	0.0	-7.4	-2.8	0.2	0.0	0.0	1.0	0.4	7.34	0.00	0.00	7.09	7.46
2	-3.4	0.0	0.0	-2.1	-1.4	0.5	0.0	0.0	0.3	0.2	7.05	0.00	0.00	7.51	7.42
3	-6.2	0.0	0.0	-2.1	-5.0	1.1	0.0	0.0	0.3	0.9	5.76	0.00	0.00	7.42	5.76
4	0.0	-4.2	-4.2	-2.8	-6.7	0.0	0.6	0.6	0.4	1.0	0.00	7.45	7.46	7.48	7.05
5	-4.1	0.0	-4.2	-1.4	-2.1	0.6	0.0	0.6	0.2	0.3	7.17	0.00	7.46	7.42	7.31
6	-11.1	-4.9	-5.0	-4.1	-2.8	1.5	0.7	0.8	0.6	0.4	7.16	7.34	6.35	6.86	7.45
7	-9.4	-19.1	-12.1	-6.5	-105.0	1.6	3.0	1.9	1.0	16.5	6.03	6.35	6.21	6.55	6.37
8	-15.2	-0.6	-0.9	-0.7	-69.6	1.9	0.1	0.2	0.1	11.2	8.20	5.63	5.32	7.64	6.24
9	-8.0	-4.9	-8.1	-10.0	-34.4	1.4	1.0	1.9	1.6	5.9	5.55	5.02	4.38	6.17	5.85
10	-13.7	-9.1	-2.7	-39.7	-4.9	2.3	1.4	0.5	6.9	0.7	5.86	6.66	5.21	5.73	7.42
11	-4.9	-5.5	-6.9	-56.0	-3.8	0.8	1.1	1.0	10.0	0.6	6.14	4.97	7.20	5.58	6.58
12	0.0	-0.5	-32.0	-38.8	-5.5	0.0	0.1	6.1	8.0	1.2	0.00	4.99	5.24	4.82	4.54
13	-17.6	-16.5	-7.0	-49.1	-4.0	3.7	3.4	1.5	10.0	0.7	4.76	4.80	4.54	4.90	5.61
14	-12.9	-12.5	-72.0	-70.7	-3.9	2.6	2.5	15.2	14.8	1.1	4.89	4.98	4.72	4.77	3.45
15	-15.6	-19.8	-27.7	-39.4	0.0	3.1	4.2	5.9	8.4	0.0	5.09	4.76	4.71	4.72	0.00
16	-8.9	-9.6	-27.3	-75.7	-9.1	1.6	1.8	5.5	15.3	1.6	5.45	5.33	4.94	4.93	5.56
17	-13.3	-12.3	-33.2	-50.1	-0.6	2.8	2.5	7.4	10.7	0.1	4.78	4.88	4.51	4.66	6.15
18	-13.8	-9.1	-22.0	-46.5	-3.8	2.8	2.3	5.2	10.4	0.6	4.86	4.04	4.27	4.49	6.49
19	-11.1	-4.6	-10.9	-43.1	0.0	1.9	0.8	1.8	8.8	0.0	5.84	5.85	5.98	4.88	0.00
20	-4.5	-14.0	-33.3	-46.3	0.0	1.1	2.8	7.1	9.7	0.0	4.15	4.95	4.73	4.77	0.00
21	-6.0	-4.5	-6.1	-23.4	0.0	1.2	0.9	1.0	4.7	0.0	5.24	4.94	6.20	4.98	0.00
22	-5.5	-9.1	-2.7	-16.4	-6.4	0.8	1.4	0.4	3.2	1.4	7.08	6.57	7.12	5.13	4.63
23	-2.9	-4.1	0.0	0.0	-4.1	0.5	0.6	0.0	0.0	0.6	5.83	6.29	0.00	0.00	7.29
24	0.0	0.0	0.0	-1.3	-8.6	0.0	0.0	0.0	0.2	1.3	0.00	0.00	0.00	6.79	6.84
TOTAL	-189	-165	-318	-634	-284	34	31	64	127	46	5.59	5.29	4.94	5.00	6.13

Figure 36. Thermal energy generated by the heat pump, electrical energy consumption of the heat pump and EER in May for different control strategies

In May, the thermal energy generated by the heat pump follows the same profile as the thermal energy provided to the building. The thermal energy produced by the heat pump is higher than the energy given to the building due to the thermal losses in the distribution circuit. In cooling mode, as there is not a climatic curve applied to the distribution circuit, the EER of the heat pump only depends on the outdoor temperature. The advanced control strategy results in lower EER if compared to the rule-based control because the load is concentrated in the central part of the day. The higher thermal load coupled with a lower EER results in higher electrical energy consumption of the heat pump. The only exception is the case with the inverted temperature because the load is shifted in the morning hours. However, because the thermal energy is higher, the electrical consumption is anyway higher than the one obtained with the rule-based control. Moreover, the shift of the load means higher thermal discomfort in the central part of the day and a lower exploitation of the PV system. In May the production of the PV system is high, and the thermal needs of the building are low, thus, there is a lot of available energy that can be exploited. Therefore, the adaption of the advanced control strategy does not increase the electrical energy withdrawn from the grid. However, in order to limit the increase of the electrical consumption it is possible to decrease the space cooling setpoint by 1 K instead of 2 K during the mild cooling season.

In July the advanced control strategy slightly increases the thermal energy provided to the building if compared to the rule-based control, except for the case with no control on the PV production where the load is significantly higher. In Figure 37 the monthly thermal energy generated (Qth), the electrical energy consumption (Wel) and the energy efficiency ratio (EER) of the heat pump in space cooling mode in May are reported.



	Qth					Wel					EER				
		RBC		AC	AC		RBC		AC	AC		RBC		AC	AC
	RBC	with night set-back	AC	no PV restriction	with inverted T	RBC	with night set-back	AC	no PV restriction	with inverted T	RBC	with night set-back	AC	no PV restriction	with inverted T
1	-74.7	0.0	-0.6	0.0	-71.9	13.8	0.0	0.1	0.0	13.2	5.40	0.00	5.74	0.00	5.44
2	-48.0	-4.5	-7.8	0.0	-54.6	8.3	0.7	1.5	0.0	9.5	5.81	6.28	5.12	0.00	5.74
3	-45.6	-6.8	-5.7	-6.3	-49.0	7.7	1.1	0.9	1.0	8.5	5.93	6.27	6.51	6.49	5.80
4	-23.8	-18.6	-3.9	-4.1	-65.6	4.0	3.0	0.6	0.6	11.3	5.88	6.14	6.67	6.35	5.80
5	-52.1	-6.4	-12.3	-7.0	-23.4	9.1	1.0	2.0	1.1	4.0	5.74	6.62	6.16	6.49	5.83
6	-42.5	-16.9	-12.4	-6.6	-36.0	7.3	2.7	2.4	1.2	6.0	5.82	6.25	5.17	5.36	6.04
7	-56.6	-242.3	-11.6	-7.5	-578.8	9.8	41.2	2.0	1.2	93.8	5.76	5.88	5.74	6.41	6.17
8	-131.8	-109.4	-21.8	-14.8	-573.6	24.3	20.4	4.0	2.6	97.2	5.43	5.36	5.48	5.65	5.90
9	-114.2	-70.6	-66.4	-28.7	-257.8	21.8	13.3	12.7	5.5	45.1	5.24	5.33	5.23	5.18	5.71
10	-75.3	-150.5	-45.3	-176.2	-15.0	14.7	31.1	9.8	32.7	2.9	5.14	4.84	4.65	5.38	5.18
11	-117.9	-108.9	-116.2	-490.5	-16.8	25.6	22.7	24.8	102.9	3.8	4.60	4.79	4.68	4.77	4.44
12	-133.1	-148.6	-371.4	-201.9	-11.8	28.9	34.1	81.1	42.6	2.8	4.61	4.35	4.58	4.74	4.23
13	-184.3	-182.0	-231.5	-316.1	-28.9	42.4	41.8	52.5	73.3	5.6	4.35	4.35	4.41	4.31	5.16
14	-170.1	-175.9	-253.6	-304.8	-5.0	41.3	42.8	59.8	70.4	1.0	4.12	4.11	4.24	4.33	4.80
15	-168.0	-182.6	-301.1	-233.9	-9.1	40.8	44.0	71.4	56.7	2.0	4.12	4.15	4.21	4.13	4.43
16	-195.6	-188.0	-220.4	-295.6	-22.4	49.8	46.4	54.8	71.1	5.5	3.93	4.05	4.02	4.16	4.08
17	-134.6	-163.8	-231.1	-256.3	-27.2	32.1	40.0	54.5	62.1	6.7	4.20	4.09	4.24	4.13	4.09
18	-133.4	-135.8	-206.7	-262.7	-22.4	34.2	34.2	48.5	60.7	5.3	3.90	3.97	4.26	4.33	4.21
19	-162.8	-166.5	-192.4	-245.3	-36.5	37.4	37.5	46.0	57.0	8.4	4.36	4.43	4.18	4.30	4.34
20	-110.6	-118.2	-140.2	-207.7	-94.6	24.7	26.8	31.9	45.5	19.8	4.48	4.42	4.40	4.57	4.77
21	-139.1	-119.3	-74.7	-178.8	-222.4	29.9	25.1	16.9	37.4	43.3	4.65	4.76	4.41	4.78	5.14
22	-70.0	-117.8	-12.3	-130.0	-212.8	14.7	24.5	2.4	26.3	45.1	4.77	4.80	5.19	4.93	4.72
23	-73.3	-22.3	-9.8	-35.9	-27.7	14.5	4.8	1.9	7.0	5.9	5.05	4.70	5.15	5.12	4.70
24	-63.2	0.0	-12.7	-3.4	-62.9	11.9	0.0	2.4	0.7	12.3	5.34	0.00	5.19	5.18	5.13
TOTAL	-2521	-2456	-2562	-3414	-2526	549	539	585	760	459	4.59	4.55	4.38	4.49	5.50

Figure 37. Thermal energy generated by the heat pump, electrical energy consumption of the heat pump and EER in July for different control strategies

Also in July, the thermal energy generated by the heat pump follows the same profile as the thermal energy provided to the building. The thermal energy produced by the heat pump is higher than the energy given to the building due to the thermal losses in the distribution circuit. The advanced control strategy results in lower EER if compared to the rule-based control because the load is concentrated in the central part of the day when the outdoor temperature is higher. The higher thermal load coupled with a lower EER results in higher electrical energy consumption of the heat pump. The only exception is the case with the inverted temperature because the load is shifted in the morning hours. However, because the thermal energy is similar and the EER is higher, the electrical consumption is lower than the one obtained with the rule-based control. However, the shift of the load means higher thermal discomfort in the central part of the day and a lower exploitation of the PV system. In July both the production of the PV system and the thermal needs of the building are high. It is not guaranteed that the PV system is always able to cover the additional electrical load. In order to limit the increase of the electrical energy withdrawn from the grid it is possible to check if the predicted PV production is higher than the forecasted building's consumption.

The EER of the heat pump in space cooling mode is lower in the central part of the day due to higher temperature at the evaporator. The advanced control strategy for space cooling proved to be able to shift the load in toward the central part of the day without significantly increasing the electrical consumption of the heat pump only during the hot cooling season. The night setbacks are not useful to shift the thermal load of the building because it is almost irrelevant during the night.

During the mild cooling season (May) the building demand is low, and the PV production is high. In this case, the advanced control logic increases the electrical consumption. However, this higher electrical energy consumption is concentrated in the central part of the day and can be covered by PV system production. If the increase of the setpoint to 1 K during the mild seasons it is possible to further reduce the electrical consumption of the heat pump. It is not meaningful to invert the temperature because of the higher thermal discomfort during the warmer part of the day.

During the hot cooling season (July) both the building demand and the PV production are high. The advanced control logic slightly increases the thermal load. Because of the lower EER, the electrical consumption is slightly higher. In the central part of the day the load should be covered with the PV. To ensure the reduction of the electricity withdrawn from the grid it is necessary to change the space heating setpoint only in the days in which the PV system is able to cover the additional load.

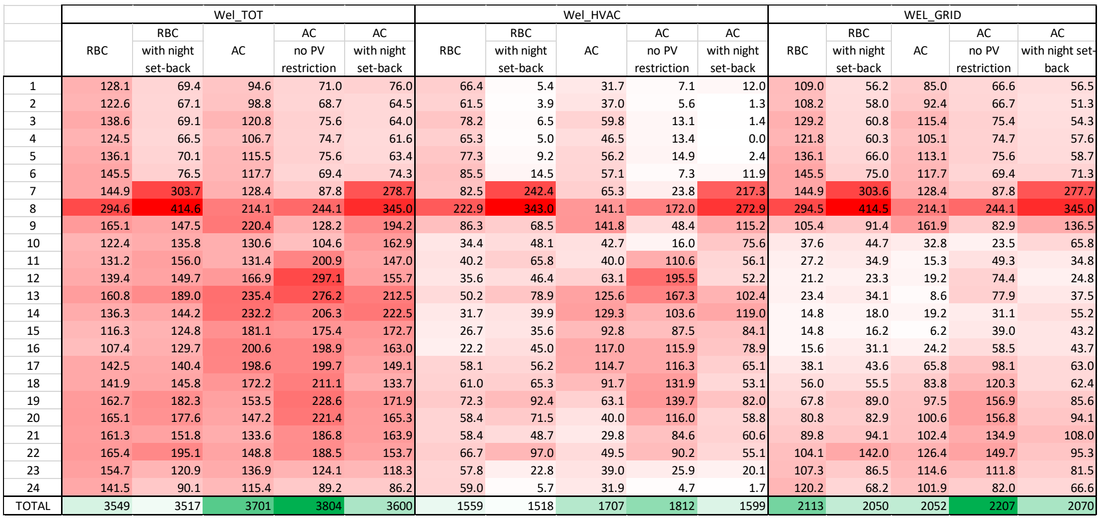
Besides the consumption of the heat pump, there are other components that influence the performance of the system and the energy balance of the system. The total energy consumption of the building is composed by the electrical consumption of the heat pump, the circulation pumps and other auxiliary systems, the emission units, the mechanical ventilation system, the ceiling fans, the lighting system and the appliances. All these consumptions should be covered by the photovoltaic system.

In this analysis, the mechanical ventilation, the lighting system and the appliances are considered fixed load that are not influenced by the control strategy.

The heat pump, the circulation pumps and other auxiliary systems, the emission units, and the ceiling fans are considered as the loads that depend on the control strategy.

Figure 38 reports the total electrical energy consumed by the building (Wel_TOT - heat pump, circulation pumps and other auxiliary systems, emission units, mechanical ventilation system, ceiling fans, lighting and appliances), the electrical energy consumed by the energy system (Wel_HVAC - heat pump, circulation pumps and other auxiliary systems, emission units and ceiling fans) and the electricity withdrawn from the grid (Wel_GRID) in January.

The values represent the monthly electrical consumption (kWh) in each hour of the day, for different control strategies. The control strategy RBC is the simple rule-based control and RBC with night set-back is the rule-based control where the space heating setpoint is lowered by 2 K between 10 PM and 6 AM. AC stands for the advanced control strategy, AC no PV restriction means that the load predictor is not used and the setpoint is shifted in any case, while AC with night set-back is the advanced control where the space heating setpoint is lowered by 2 K between 10 PM and 6 AM. AC with inverted T is the advanced control where the space cooling setpoint is lowered by 2 K when the outdoor temperature is lower than the predicted daily average temperature.

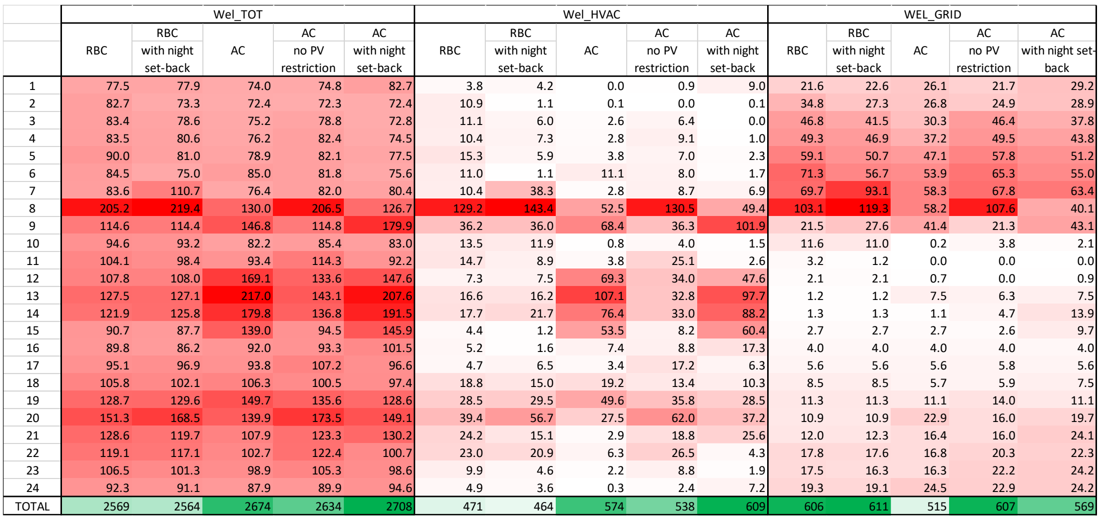


	Wel_TOT					Wel_HVAC					WEL_GRID				
	RBC	RBC with night set-back	AC	AC no PV restriction	AC with night set-back	RBC	RBC with night set-back	AC	AC no PV restriction	AC with night set-back	RBC	RBC with night set-back	AC	AC no PV restriction	AC with night set-back
1	128.1	69.4	94.6	71.0	76.0	66.4	5.4	31.7	7.1	12.0	109.0	56.2	85.0	66.6	56.5
2	122.6	67.1	98.8	68.7	64.5	61.5	3.9	37.0	5.6	1.3	108.2	58.0	92.4	66.7	51.3
3	138.6	69.1	120.8	75.6	64.0	78.2	6.5	59.8	13.1	1.4	129.2	60.8	115.4	75.4	54.3
4	124.5	66.5	106.7	74.7	61.6	65.3	5.0	46.5	13.4	0.0	121.8	60.3	105.1	74.7	57.6
5	136.1	70.1	115.5	75.6	63.4	77.3	9.2	56.2	14.9	2.4	136.1	66.0	113.1	75.6	58.7
6	145.5	76.5	117.7	69.4	74.3	85.5	14.5	57.1	7.3	11.9	145.5	75.0	117.7	69.4	71.3
7	144.9	303.7	128.4	87.8	278.7	82.5	242.4	65.3	23.8	217.3	144.9	303.6	128.4	87.8	277.7
8	294.6	414.6	214.1	244.1	345.0	222.9	343.0	141.1	172.0	272.9	294.5	414.5	214.1	244.1	345.0
9	165.1	147.5	220.4	128.2	194.2	86.3	68.5	141.8	48.4	115.2	105.4	91.4	161.9	82.9	136.5
10	122.4	135.8	130.6	104.6	162.9	34.4	48.1	42.7	16.0	75.6	37.6	44.7	32.8	23.5	65.8
11	131.2	156.0	131.4	200.9	147.0	40.2	65.8	40.0	110.6	56.1	27.2	34.9	15.3	49.3	34.8
12	139.4	149.7	166.9	297.1	155.7	35.6	46.4	63.1	195.5	52.2	21.2	23.3	19.2	74.4	24.8
13	160.8	189.0	235.4	276.2	212.5	50.2	78.9	125.6	167.3	102.4	23.4	34.1	8.6	77.9	37.5
14	136.3	144.2	232.2	206.3	222.5	31.7	39.9	129.3	103.6	119.0	14.8	18.0	19.2	31.1	55.2
15	116.3	124.8	181.1	175.4	172.7	26.7	35.6	92.8	87.5	84.1	14.8	16.2	6.2	39.0	43.2
16	107.4	129.7	200.6	198.9	163.0	22.2	45.0	117.0	115.9	78.9	15.6	31.1	24.2	58.5	43.7
17	142.5	140.4	198.6	199.7	149.1	58.1	56.2	114.7	116.3	65.1	38.1	43.6	65.8	98.1	63.0
18	141.9	145.8	172.2	211.1	133.7	61.0	65.3	91.7	131.9	53.1	56.0	55.5	83.8	120.3	62.4
19	162.7	182.3	153.5	228.6	171.9	72.3	92.4	63.1	139.7	82.0	67.8	89.0	97.5	156.9	85.6
20	165.1	177.6	147.2	221.4	165.3	58.4	71.5	40.0	116.0	58.8	80.8	82.9	100.6	156.8	94.1
21	161.3	151.8	133.6	186.8	163.9	58.4	48.7	29.8	84.6	60.6	89.8	94.1	102.4	134.9	108.0
22	165.4	195.1	148.8	188.5	153.7	66.7	97.0	49.5	90.2	55.1	104.1	142.0	126.4	149.7	95.3
23	154.7	120.9	136.9	124.1	118.3	57.8	22.8	39.0	25.9	20.1	107.3	86.5	114.6	111.8	81.5
24	141.5	90.1	115.4	89.2	86.2	59.0	5.7	31.9	4.7	1.7	120.2	68.2	101.9	82.0	66.6
TOTAL	3549	3517	3701	3804	3600	1559	1518	1707	1812	1599	2113	2050	2052	2207	2070

Figure 38. Total electrical consumption, electrical consumption of HVAC and electricity withdrawn from the grid in January for the different control strategies

The electrical energy consumed by the energy system represent less than 50% of the total energy consumption. This means that more than half of the consumption is due to fixed loads that are not affected by the control strategy. The advanced control strategy shifts the electrical consumptions of the energy system toward the central part of the day. The night setbacks, move the loads from the night to the first hours of the morning. The advanced control logic increases the total electrical energy consumption. The increase is equal to the increase of the energy system consumption. Nevertheless, the increase of the consumption of the energy system does not mean an increase of the electricity withdrawn from the grid. Due to the shift of the consumption, it is possible to cover the additional load. In fact, the advanced control strategy presents the lower amount of electricity withdrawn from the grid. Most of the electricity is withdrawn from the grid in the evening and in the morning, but even during the day there is the need to integrate some energy taken from the grid. This implies that the PV and battery system is neither able to produce nor to store enough energy to satisfy the building's consumptions in January. For this reason, it is important to forecast the building's consumptions and the PV production, in order to shift the setpoints only when it is convenient to do it. In order to completely cover the building's consumptions in January it is necessary to increase the size of both the PV and battery. This implies a higher investment cost and the need more surfaces where PV panels can be installed.

Figure 39 reports the total electrical energy consumed by the building (Wel_TOT), the electrical energy consumed by the energy system (Wel_HVAC) and the electricity withdrawn from the grid (Wel_GRID) in March.

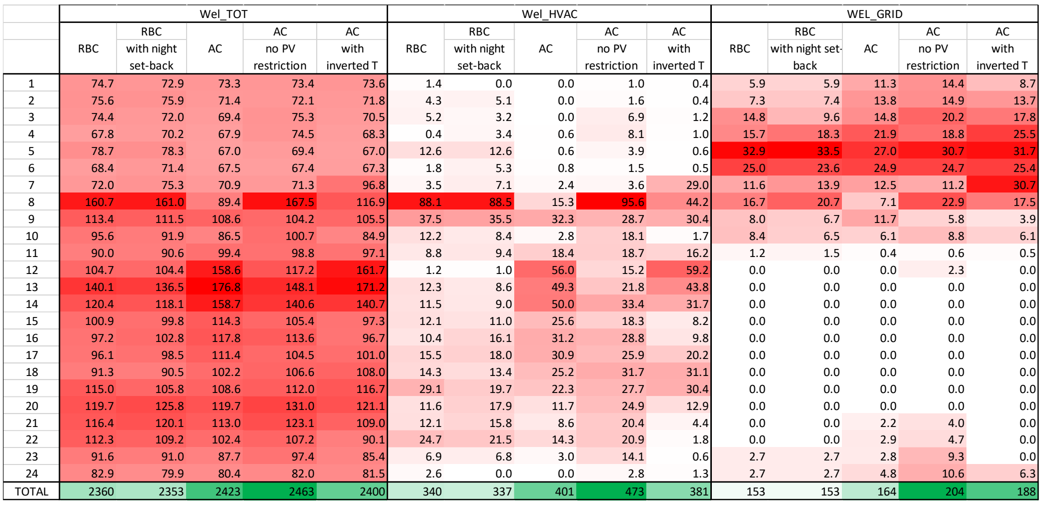


	Wel_TOT					Wel_HVAC					WEL_GRID				
	RBC	RBC with night set-back	AC	AC no PV restriction	AC with night set-back	RBC	RBC with night set-back	AC	AC no PV restriction	AC with night set-back	RBC	RBC with night set-back	AC	AC no PV restriction	AC with night set-back
1	77.5	77.9	74.0	74.8	82.7	3.8	4.2	0.0	0.9	9.0	21.6	22.6	26.1	21.7	29.2
2	82.7	73.3	72.4	72.3	72.4	10.9	1.1	0.1	0.0	0.1	34.8	27.3	26.8	24.9	28.9
3	83.4	78.6	75.2	78.8	72.8	11.1	6.0	2.6	6.4	0.0	46.8	41.5	30.3	46.4	37.8
4	83.5	80.6	76.2	82.4	74.5	10.4	7.3	2.8	9.1	1.0	49.3	46.9	37.2	49.5	43.8
5	90.0	81.0	78.9	82.1	77.5	15.3	5.9	3.8	7.0	2.3	59.1	50.7	47.1	57.8	51.2
6	84.5	75.0	85.0	81.8	75.6	11.0	1.1	11.1	8.0	1.7	71.3	56.7	53.9	65.3	55.0
7	83.6	110.7	76.4	82.0	80.4	10.4	38.3	2.8	8.7	6.9	69.7	93.1	58.3	67.8	63.4
8	205.2	219.4	130.0	206.5	126.7	129.2	143.4	52.5	130.5	49.4	103.1	119.3	58.2	107.6	40.1
9	114.6	114.4	146.8	114.8	179.9	36.2	36.0	68.4	36.3	101.9	21.5	27.6	41.4	21.3	43.1
10	94.6	93.2	82.2	85.4	83.0	13.5	11.9	0.8	4.0	1.5	11.6	11.0	0.2	3.8	2.1
11	104.1	98.4	93.4	114.3	92.2	14.7	8.9	3.8	25.1	2.6	3.2	1.2	0.0	0.0	0.0
12	107.8	108.0	169.1	133.6	147.6	7.3	7.5	69.3	34.0	47.6	2.1	2.1	0.7	0.0	0.9
13	127.5	127.1	217.0	143.1	207.6	16.6	16.2	107.1	32.8	97.7	1.2	1.2	7.5	6.3	7.5
14	121.9	125.8	179.8	136.8	191.5	17.7	21.7	76.4	33.0	88.2	1.3	1.3	1.1	4.7	13.9
15	90.7	87.7	139.0	94.5	145.9	4.4	1.2	53.5	8.2	60.4	2.7	2.7	2.7	2.6	9.7
16	89.8	86.2	92.0	93.3	101.5	5.2	1.6	7.4	8.8	17.3	4.0	4.0	4.0	4.0	4.0
17	95.1	96.9	93.8	107.2	96.6	4.7	6.5	3.4	17.2	6.3	5.6	5.6	5.6	5.8	5.6
18	105.8	102.1	106.3	100.5	97.4	18.8	15.0	19.2	13.4	10.3	8.5	8.5	5.7	5.9	7.5
19	128.7	129.6	149.7	135.6	128.6	28.5	29.5	49.6	35.8	28.5	11.3	11.3	11.1	14.0	11.1
20	151.3	168.5	139.9	173.5	149.1	39.4	56.7	27.5	62.0	37.2	10.9	10.9	22.9	16.0	19.7
21	128.6	119.7	107.9	123.3	130.2	24.2	15.1	2.9	18.8	25.6	12.0	12.3	16.4	16.0	24.1
22	119.1	117.1	102.7	122.4	100.7	23.0	20.9	6.3	26.5	4.3	17.8	17.6	16.8	20.3	22.3
23	106.5	101.3	98.9	105.3	98.6	9.9	4.6	2.2	8.8	1.9	17.5	16.3	16.3	22.2	24.2
24	92.3	91.1	87.9	89.9	94.6	4.9	3.6	0.3	2.4	7.2	19.3	19.1	24.5	22.9	24.2
TOTAL	2569	2564	2674	2634	2708	471	464	574	538	609	606	611	515	607	569

Figure 39. Total electrical consumption, electrical consumption of HVAC and electricity withdrawn from the grid in March for the different control strategies

The electrical energy consumed by the energy system in March is about 20% of the total energy consumption. The same trends seen for the January data are shown for March. The only difference is that the electrical energy withdrawn from the grid during the day is negligible. This implies that the PV system is able to produce enough energy to cover the consumptions during the central part of the day, but it is not possible to store enough energy to cover the consumptions during the rest of the day.

Figure 40 reports the total electrical energy consumed by the building (Wel_TOT), the electrical energy consumed by the energy system (Wel_HVAC) and the electricity withdrawn from the grid (Wel_GRID) in May.

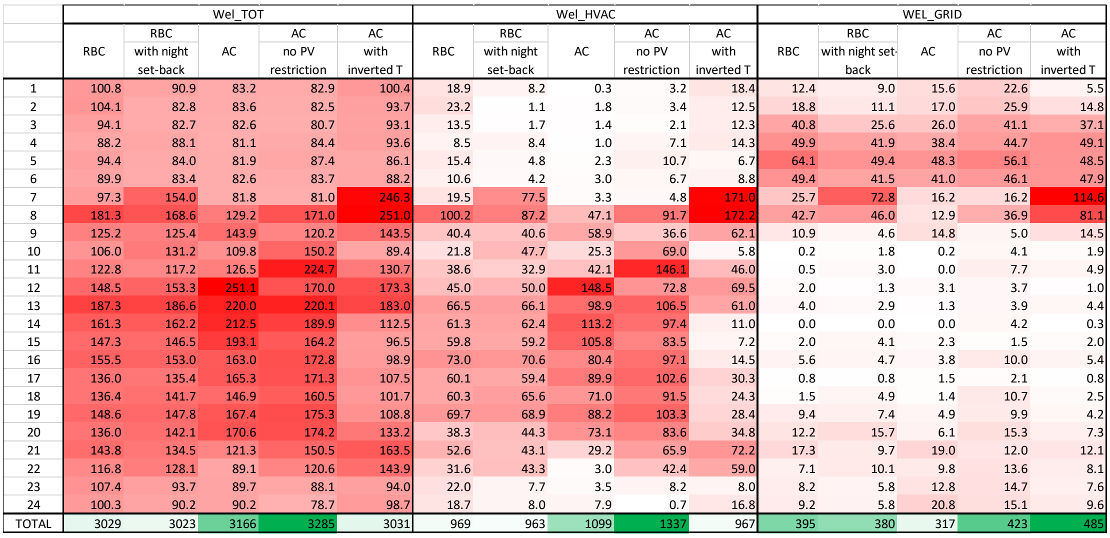


	Wel_TOT					Wel_HVAC					WEL_GRID				
	RBC	RBC with night set-back	AC	AC no PV restriction	AC with inverted T	RBC	RBC with night set-back	AC	AC no PV restriction	AC with inverted T	RBC	RBC with night set-back	AC	AC no PV restriction	AC with inverted T
1	74.7	72.9	73.3	73.4	73.6	1.4	0.0	0.0	1.0	0.4	5.9	5.9	11.3	14.4	8.7
2	75.6	75.9	71.4	72.1	71.8	4.3	5.1	0.0	1.6	0.4	7.3	7.4	13.8	14.9	13.7
3	74.4	72.0	69.4	75.3	70.5	5.2	3.2	0.0	6.9	1.2	14.8	9.6	14.8	20.2	17.8
4	67.8	70.2	67.9	74.5	68.3	0.4	3.4	0.6	8.1	1.0	15.7	18.3	21.9	18.8	25.5
5	78.7	78.3	67.0	69.4	67.0	12.6	12.6	0.6	3.9	0.6	32.9	33.5	27.0	30.7	31.7
6	68.4	71.4	67.5	67.4	67.3	1.8	5.3	0.8	1.5	0.5	25.0	23.6	24.9	24.7	25.4
7	72.0	75.3	70.9	71.3	96.8	3.5	7.1	2.4	3.6	29.0	11.6	13.9	12.5	11.2	30.7
8	160.7	161.0	89.4	167.5	116.9	88.1	88.5	15.3	95.6	44.2	16.7	20.7	7.1	22.9	17.5
9	113.4	111.5	108.6	104.2	105.5	37.5	35.5	32.3	28.7	30.4	8.0	6.7	11.7	5.8	3.9
10	95.6	91.9	86.5	100.7	84.9	12.2	8.4	2.8	18.1	1.7	8.4	6.5	6.1	8.8	6.1
11	90.0	90.6	99.4	98.8	97.1	8.8	9.4	18.4	18.7	16.2	1.2	1.5	0.4	0.6	0.5
12	104.7	104.4	158.6	117.2	161.7	1.2	1.0	56.0	15.2	59.2	0.0	0.0	0.0	2.3	0.0
13	140.1	136.5	176.8	148.1	171.2	12.3	8.6	49.3	21.8	43.8	0.0	0.0	0.0	0.0	0.0
14	120.4	118.1	158.7	140.6	140.7	11.5	9.0	50.0	33.4	31.7	0.0	0.0	0.0	0.0	0.0
15	100.9	99.8	114.3	105.4	97.3	12.1	11.0	25.6	18.3	8.2	0.0	0.0	0.0	0.0	0.0
16	97.2	102.8	117.8	113.6	96.7	10.4	16.1	31.2	28.8	9.8	0.0	0.0	0.0	0.0	0.0
17	96.1	98.5	111.4	104.5	101.0	15.5	18.0	30.9	25.9	20.2	0.0	0.0	0.0	0.0	0.0
18	91.3	90.5	102.2	106.6	108.0	14.3	13.4	25.2	31.7	31.1	0.0	0.0	0.0	0.0	0.0
19	115.0	105.8	108.6	112.0	116.7	29.1	19.7	22.3	27.7	30.4	0.0	0.0	0.0	0.0	0.0
20	119.7	125.8	119.7	131.0	121.1	11.6	17.9	11.7	24.9	12.9	0.0	0.0	0.0	0.0	0.0
21	116.4	120.1	113.0	123.1	109.0	12.1	15.8	8.6	20.4	4.4	0.0	0.0	2.2	4.0	0.0
22	112.3	109.2	102.4	107.2	90.1	24.7	21.5	14.3	20.9	1.8	0.0	0.0	2.9	4.7	0.0
23	91.6	91.0	87.7	97.4	85.4	6.9	6.8	3.0	14.1	0.6	2.7	2.7	2.8	9.3	0.0
24	82.9	79.9	80.4	82.0	81.5	2.6	0.0	0.0	2.8	1.3	2.7	2.7	4.8	10.6	6.3
TOTAL	2360	2353	2423	2463	2400	340	337	401	473	381	153	153	164	204	188

Figure 40. Total electrical consumption, electrical consumption of HVAC and electricity withdrawn from the grid in May for the different control strategies

The electrical energy consumed by the energy system in May is about 15% of the total energy consumption. In May the advanced control strategy increases the total electrical consumption, the consumption of the energy system and slightly the electrical energy withdrawn from the grid. However, almost the entire withdrawn electricity is taken in the first part of the day when the PV system is not producing anything. This implies that the battery is not able to store enough energy during the day to cover the building's consumptions in the first part of the day.

Figure 40 reports the total electrical energy consumed by the building (Wel_TOT), the electrical energy consumed by the energy system (Wel_HVAC) and the electricity withdrawn from the grid (Wel_GRID) in July.

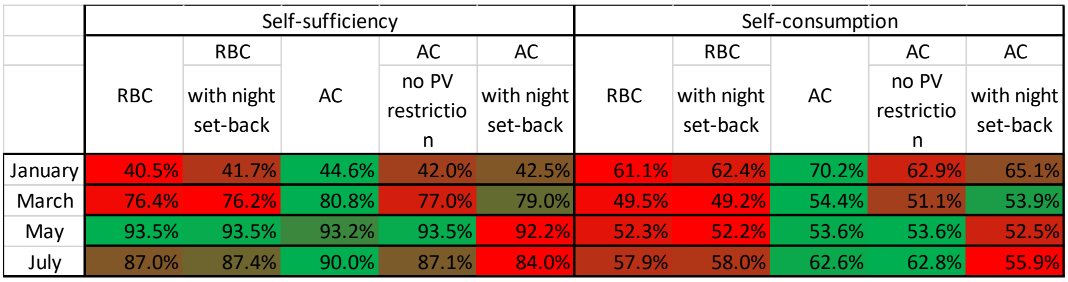


	Wel_TOT					Wel_HVAC					WEL_GRID				
	RBC	RBC with night set-back	AC	AC no PV restriction	AC with inverted T	RBC	RBC with night set-back	AC	AC no PV restriction	AC with inverted T	RBC	RBC with night set-back	AC	AC no PV restriction	AC with inverted T
1	100.8	90.9	83.2	82.9	100.4	18.9	8.2	0.3	3.2	18.4	12.4	9.0	15.6	22.6	5.5
2	104.1	82.8	83.6	82.5	93.7	23.2	1.1	1.8	3.4	12.5	18.8	11.1	17.0	25.9	14.8
3	94.1	82.7	82.6	80.7	93.1	13.5	1.7	1.4	2.1	12.3	40.8	25.6	26.0	41.1	37.1
4	88.2	88.1	81.1	84.4	93.6	8.5	8.4	1.0	7.1	14.3	49.9	41.9	38.4	44.7	49.1
5	94.4	84.0	81.9	87.4	86.1	15.4	4.8	2.3	10.7	6.7	64.1	49.4	48.3	56.1	48.5
6	89.9	83.4	82.6	83.7	88.2	10.6	4.2	3.0	6.7	8.8	49.4	41.5	41.0	46.1	47.9
7	97.3	154.0	81.8	81.0	246.3	19.5	77.5	3.3	4.8	171.0	25.7	72.8	16.2	16.2	114.6
8	181.3	168.6	129.2	171.0	251.0	100.2	87.2	47.1	91.7	172.2	42.7	46.0	12.9	36.9	81.1
9	125.2	125.4	143.9	120.2	143.5	40.4	40.6	58.9	36.6	62.1	10.9	4.6	14.8	5.0	14.5
10	106.0	131.2	109.8	150.2	89.4	21.8	47.7	25.3	69.0	5.8	0.2	1.8	0.2	4.1	1.9
11	122.8	117.2	126.5	224.7	130.7	38.6	32.9	42.1	146.1	46.0	0.5	3.0	0.0	7.7	4.9
12	148.5	153.3	251.1	170.0	173.3	45.0	50.0	148.5	72.8	69.5	2.0	1.3	3.1	3.7	1.0
13	187.3	186.6	220.0	220.1	183.0	66.5	66.1	98.9	106.5	61.0	4.0	2.9	1.3	3.9	4.4
14	161.3	162.2	212.5	189.9	112.5	61.3	62.4	113.2	97.4	11.0	0.0	0.0	0.0	4.2	0.3
15	147.3	146.5	193.1	164.2	96.5	59.8	59.2	105.8	83.5	7.2	2.0	4.1	2.3	1.5	2.0
16	155.5	153.0	163.0	172.8	98.9	73.0	70.6	80.4	97.1	14.5	5.6	4.7	3.8	10.0	5.4
17	136.0	135.4	165.3	171.3	107.5	60.1	59.4	89.9	102.6	30.3	0.8	0.8	1.5	2.1	0.8
18	136.4	141.7	146.9	160.5	101.7	60.3	65.6	71.0	91.5	24.3	1.5	4.9	1.4	10.7	2.5
19	148.6	147.8	167.4	175.3	108.8	69.7	68.9	88.2	103.3	28.4	9.4	7.4	4.9	9.9	4.2
20	136.0	142.1	170.6	174.2	133.2	38.3	44.3	73.1	83.6	34.8	12.2	15.7	6.1	15.3	7.3
21	143.8	134.5	121.3	150.5	163.5	52.6	43.1	29.2	65.9	72.2	17.3	9.7	19.0	12.0	12.1
22	116.8	128.1	89.1	120.6	143.9	31.6	43.3	3.0	42.4	59.0	7.1	10.1	9.8	13.6	8.1
23	107.4	93.7	89.7	88.1	94.0	22.0	7.7	3.5	8.2	8.0	8.2	5.8	12.8	14.7	7.6
24	100.3	90.2	90.2	78.7	98.7	18.7	8.0	7.9	0.7	16.8	9.2	5.8	20.8	15.1	9.6
TOTAL	3029	3023	3166	3285	3031	969	963	1099	1337	967	395	380	317	423	485

Figure 41. Total electrical consumption, electrical consumption of HVAC and electricity withdrawn from the grid in July for the different control strategies

In July, the electrical energy consumed by the energy system represent less than 35% of the total energy consumption. The advanced control strategy shifts the electrical consumptions of the energy system toward the central part of the day. The advanced control logic increases the total electrical energy consumption and the consumption of energy system. Nevertheless, the increase of the consumption of the energy system does not mean an increase of the electricity withdrawn from the grid. Due to the shift of the consumption, it is possible to cover the additional load. In fact, the advanced control strategy presents the lower amount of electricity withdrawn from the grid. Most of the electricity is withdrawn from the grid in the morning. This implies that the PV system is able to produce enough energy, but it is not possible to store enough energy to cover the morning load.

Figure 42 shows the self-sufficiency and the self-consumption of the energy system with different control strategies for the reference months.



	Self-sufficiency					Self-consumption				
	RBC	RBC with night set-back	AC	AC no PV restriction	AC with night set-back	RBC	RBC with night set-back	AC	AC no PV restriction	AC with night set-back
January	40.5%	41.7%	44.6%	42.0%	42.5%	61.1%	62.4%	70.2%	62.9%	65.1%
March	76.4%	76.2%	80.8%	77.0%	79.0%	49.5%	49.2%	54.4%	51.1%	53.9%
May	93.5%	93.5%	93.2%	93.5%	92.2%	52.3%	52.2%	53.6%	53.6%	52.5%
July	87.0%	87.4%	90.0%	87.1%	84.0%	57.9%	58.0%	62.6%	62.8%	55.9%

Figure 42. Self-sufficiency and self-consumption of the energy system with different control strategies

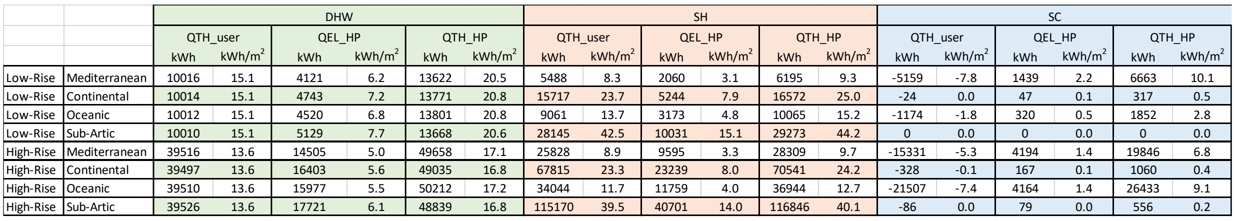
The advanced control strategy presents the higher values in terms of self-sufficiency and self-consumption. The self-sufficiency in January is below 50%, meaning that the PV system is not able to produce enough energy. Nevertheless, the self-consumption is not 100%. This is due to the losses caused by the inverter and the rectifier and due to some energy, that is sent to the grid. For the other months the self sufficiency increases (up to almost 95%) while the self-consumption decreases. This means that the PV system is able to generate enough energy to cover the building’s consumption but the battery is not able to store enough energy to cover the building’s load during the period in which there is no PV production.

The consumptions due to the energy system are a minor part of the total energy consumption of the building. Appliances represent a consistent part of the total energy consumption and it is not possible to control them. It is up to the user to understand when it is more convenient to use the appliances. The only thing that the control strategy can do is to notify the user when there is an overproduction of electricity from the PV system.

3.3.2 Comparison of annual results with rule-based and advanced control

The rule-based and advanced control logics were applied to the two building archetypes and the four geo-clusters. The comparison between the two control logics is made on the annual results.

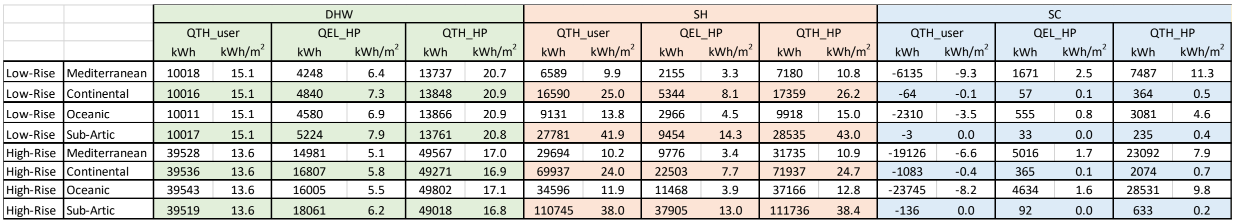
Figure 43 reports the annual results for the eight combinations of buildings archetypes and geo-clusters obtained with the rule-based control. The considered quantities are the thermal energy provided to the building (QTH_user), the electrical energy consumed by the heat pump (QEL_HP) and the thermal energy generated by the heat pump (QTH_HP). These quantities are calculated for the domestic hot water production (DHW), space heating (SH) and space cooling (SC).



		DHW						SH						SC					
		QTH_user		QEL_HP		QTH_HP		QTH_user		QEL_HP		QTH_HP		QTH_user		QEL_HP		QTH_HP	
		kWh	kWh/m^2	kWh	kWh/m^2	kWh	kWh/m^2	kWh	kWh/m^2	kWh	kWh/m^2	kWh	kWh/m^2	kWh	kWh/m^2	kWh	kWh/m^2	kWh	kWh/m^2
Low-Rise	Mediterranean	10016	15.1	4121	6.2	13622	20.5	5488	8.3	2060	3.1	6195	9.3	-5159	-7.8	1439	2.2	6663	10.1
Low-Rise	Continental	10014	15.1	4743	7.2	13771	20.8	15717	23.7	5244	7.9	16572	25.0	-24	0.0	47	0.1	317	0.5
Low-Rise	Oceanic	10012	15.1	4520	6.8	13801	20.8	9061	13.7	3173	4.8	10065	15.2	-1174	-1.8	320	0.5	1852	2.8
Low-Rise	Sub-Artic	10010	15.1	5129	7.7	13668	20.6	28145	42.5	10031	15.1	29273	44.2	0	0.0	0	0.0	0	0.0
High-Rise	Mediterranean	39516	13.6	14505	5.0	49658	17.1	25828	8.9	9595	3.3	28309	9.7	-15331	-5.3	4194	1.4	19846	6.8
High-Rise	Continental	39497	13.6	16403	5.6	49035	16.8	67815	23.3	23239	8.0	70541	24.2	-328	-0.1	167	0.1	1060	0.4
High-Rise	Oceanic	39510	13.6	15977	5.5	50212	17.2	34044	11.7	11759	4.0	36944	12.7	-21507	-7.4	4164	1.4	26433	9.1
High-Rise	Sub-Artic	39526	13.6	17721	6.1	48839	16.8	115170	39.5	40701	14.0	116846	40.1	-86	0.0	79	0.0	556	0.2

Figure 43. Annual thermal and electrical energy for DHW, SH and SC – rule-based control

Figure 44 reports same data obtained with the advanced control.



		DHW						SH						SC					
		QTH_user		QEL_HP		QTH_HP		QTH_user		QEL_HP		QTH_HP		QTH_user		QEL_HP		QTH_HP	
		kWh	kWh/m^2	kWh	kWh/m^2	kWh	kWh/m^2	kWh	kWh/m^2	kWh	kWh/m^2	kWh	kWh/m^2	kWh	kWh/m^2	kWh	kWh/m^2	kWh	kWh/m^2
Low-Rise	Mediterranean	10018	15.1	4248	6.4	13737	20.7	6589	9.9	2155	3.3	7180	10.8	-6135	-9.3	1671	2.5	7487	11.3
Low-Rise	Continental	10016	15.1	4840	7.3	13848	20.9	16590	25.0	5344	8.1	17359	26.2	-64	-0.1	57	0.1	364	0.5
Low-Rise	Oceanic	10011	15.1	4580	6.9	13866	20.9	9131	13.8	2966	4.5	9918	15.0	-2310	-3.5	555	0.8	3081	4.6
Low-Rise	Sub-Artic	10017	15.1	5224	7.9	13761	20.8	27781	41.9	9454	14.3	28535	43.0	-3	0.0	33	0.0	235	0.4
High-Rise	Mediterranean	39528	13.6	14981	5.1	49567	17.0	29694	10.2	9776	3.4	31735	10.9	-19126	-6.6	5016	1.7	23092	7.9
High-Rise	Continental	39536	13.6	16807	5.8	49271	16.9	69937	24.0	22503	7.7	71937	24.7	-1083	-0.4	365	0.1	2074	0.7
High-Rise	Oceanic	39543	13.6	16005	5.5	49802	17.1	34596	11.9	11468	3.9	37166	12.8	-23745	-8.2	4634	1.6	28531	9.8
High-Rise	Sub-Artic	39519	13.6	18061	6.2	49018	16.8	110745	38.0	37905	13.0	111736	38.4	-136	0.0	92	0.0	633	0.2

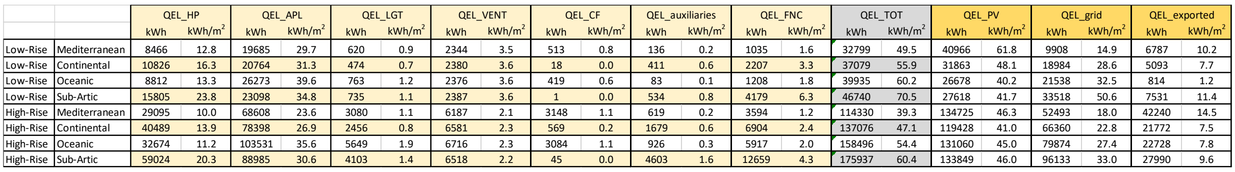
Figure 44. Annual thermal and electrical energy for DHW, SH and SC – advanced control

The thermal energy provided to the building for domestic hot water does not change by changing the control strategy. This is because the domestic hot water withdrawal profile remains the same. The thermal energy generated by the heat pump is slightly higher with the advanced control strategy. The difference is higher for warmer climates where the setpoints are shifted more often due to a higher PV production and lower consumption during the heating season. The electrical energy consumed by the heat pump increases as well. As a result, the seasonal coefficient of performance is reduced by 1% to 3%.

The space heating demand of the building increases for all climates except for the Sub-Artic. The increase is higher for climates with a higher PV production. The highest increase happens for the Low-Rise building in the Mediterranean climate (20%). The same increase can be seen for the thermal energy generated by the heat pump. The increase of the electrical consumption of the heat pump is restricted (even negative for the Oceanic and the Sub-Artic climates). This results in higher seasonal coefficients of performance. The increase varies between 3% and 11%.

Also the space cooling demand of the building is higher with the advanced control strategy. The increase is particularly high for the Low-Rise building in the Oceanic climate. The same increase for both the thermal energy generated and the electrical energy consumed by the heat pump. As a result, the seasonal energy efficiency ratio decreases.

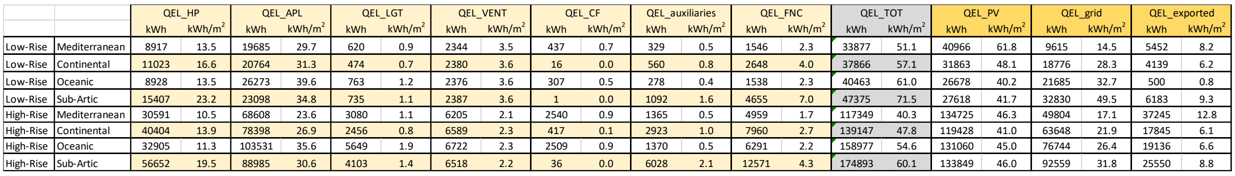
Figure 45 reports the annual electrical energy consumption of the building (QEL_TOT) obtained with the rule-based control. The total consumption is the sum of the electrical consumption of the heat pump (QEL_HP), the appliances (QEL_APL), the lighting (QEL_LGT), the mechanical ventilation (QEL_VENT), the ceiling fans (QEL_CF), the circulation pump and other auxiliary system (QEL_AUX) and the emission units (QEL_FNC). Moreover, the gross electric energy production of the PV system (QEL_PV), the electricity withdrawn from the grid (QEL_grid) and the electricity sent to the grid (QEL_exported) are reported. The data are reported for each combination of building archetype and geo-cluster.



		QEL_HP		QEL_APL		QEL_LGT		QEL_VENT		QEL_CF		QEL_auxiliaries		QEL_FNC		QEL_TOT		QEL_PV		QEL_grid		QEL_exported	
		kWh	kWh/m^2	kWh	kWh/m^2	kWh	kWh/m^2	kWh	kWh/m^2	kWh	kWh/m^2	kWh	kWh/m^2	kWh	kWh/m^2	kWh	kWh/m^2	kWh	kWh/m^2	kWh	kWh/m^2	kWh	kWh/m^2
Low-Rise	Mediterranean	8466	12.8	19685	29.7	620	0.9	2344	3.5	513	0.8	136	0.2	1035	1.6	32799	49.5	40966	61.8	9908	14.9	6787	10.2
Low-Rise	Continental	10826	16.3	20764	31.3	474	0.7	2380	3.6	18	0.0	411	0.6	2207	3.3	37079	55.9	31863	48.1	18984	28.6	5093	7.7
Low-Rise	Oceanic	8812	13.3	26273	39.6	763	1.2	2376	3.6	419	0.6	83	0.1	1208	1.8	39935	60.2	26678	40.2	21538	32.5	814	1.2
Low-Rise	Sub-Artic	15805	23.8	23098	34.8	735	1.1	2387	3.6	1	0.0	534	0.8	4179	6.3	46740	70.5	27618	41.7	33518	50.6	7531	11.4
High-Rise	Mediterranean	29095	10.0	68608	23.6	3080	1.1	6187	2.1	3148	1.1	619	0.2	3594	1.2	114330	39.3	134725	46.3	52493	18.0	42240	14.5
High-Rise	Continental	40489	13.9	78398	26.9	2456	0.8	6581	2.3	569	0.2	1679	0.6	6904	2.4	137076	47.1	119428	41.0	66360	22.8	21772	7.5
High-Rise	Oceanic	32674	11.2	103531	35.6	5649	1.9	6716	2.3	3084	1.1	926	0.3	5917	2.0	158496	54.4	131060	45.0	79874	27.4	22728	7.8
High-Rise	Sub-Artic	59024	20.3	88985	30.6	4103	1.4	6518	2.2	45	0.0	4603	1.6	12659	4.3	175937	60.4	133849	46.0	96133	33.0	27990	9.6

Figure 45. Annual electrical consumptions for rule-based control

Figure 46 reports same data obtained with the advanced control.



		QEL_HP		QEL_APL		QEL_LGT		QEL_VENT		QEL_CF		QEL_auxiliaries		QEL_FNC		QEL_TOT		QEL_PV		QEL_grid		QEL_exported	
		kWh	kWh/m^2	kWh	kWh/m^2	kWh	kWh/m^2	kWh	kWh/m^2	kWh	kWh/m^2	kWh	kWh/m^2	kWh	kWh/m^2	kWh	kWh/m^2	kWh	kWh/m^2	kWh	kWh/m^2	kWh	kWh/m^2
Low-Rise	Mediterranean	8917	13.5	19685	29.7	620	0.9	2344	3.5	437	0.7	329	0.5	1546	2.3	33877	51.1	40966	61.8	9615	14.5	5452	8.2
Low-Rise	Continental	11023	16.6	20764	31.3	474	0.7	2380	3.6	16	0.0	560	0.8	2648	4.0	37866	57.1	31863	48.1	18776	28.3	4139	6.2
Low-Rise	Oceanic	8928	13.5	26273	39.6	763	1.2	2376	3.6	307	0.5	278	0.4	1538	2.3	40463	61.0	26678	40.2	21685	32.7	500	0.8
Low-Rise	Sub-Artic	15407	23.2	23098	34.8	735	1.1	2387	3.6	1	0.0	1092	1.6	4655	7.0	47375	71.5	27618	41.7	32830	49.5	6183	9.3
High-Rise	Mediterranean	30591	10.5	68608	23.6	3080	1.1	6205	2.1	2540	0.9	1365	0.5	4959	1.7	117349	40.3	134725	46.3	49804	17.1	37245	12.8
High-Rise	Continental	40404	13.9	78398	26.9	2456	0.8	6589	2.3	417	0.1	2923	1.0	7960	2.7	139147	47.8	119428	41.0	63648	21.9	17845	6.1
High-Rise	Oceanic	32905	11.3	103531	35.6	5649	1.9	6722	2.3	2509	0.9	1370	0.5	6291	2.2	158977	54.6	131060	45.0	76744	26.4	19136	6.6
High-Rise	Sub-Artic	56652	19.5	88985	30.6	4103	1.4	6518	2.2	36	0.0	6028	2.1	12571	4.3	174893	60.1	133849	46.0	92559	31.8	25550	8.8

Figure 46. Annual electrical consumptions for advanced control

The electrical consumption of the heat pump increases with the advanced control logic. The increase is higher for warmer climates where the PV production is higher. The increase does not exceed 5%. The electrical energy consumptions due to appliances, lighting and ventilation are the same as these quantities are not affected by the change of the control logics. Because the space cooling setpoint is decreased during summer, the electrical consumption of the ceiling fans is lower with the advanced control logic.

Both the electrical energy consumption the circulating pumps, auxiliary systems and emission units (fan coils) are higher because they work for a greater number of hours. As a result, the total annual electrical energy consumption obtained with the advanced is between 1% and 3% higher than the consumption obtained with the rule-based control. Nevertheless, even if the annual electricity produced by the PV system is the same, with the advanced control strategy the electrical energy withdrawn from the grid is lower (about 5%). The savings are up to 2700 kWh for the High-Rise building in the Mediterranean climate. At the same time, also the amount of electricity sent to the grid is lower. This means that the advanced control strategy allows to reduce the electrical energy withdrawn from the grid, while increasing both the self-sufficiency and the self-consumption.

		Low-Rise				High-Rise			
		Mediterranean	Continental	Oceanic	Sub-Artic	Mediterranean	Continental	Oceanic	Sub-Artic
Primary energy conversion factor	[-]	2.42	1.37	2.3	2.28	2.42	1.37	2.3	2.28
national %renewable in grid	[-]	0.398	0.457	0.236	0.95	0.398	0.457	0.236	0.95
Primary energy	[kWh/m^2]	70.7	66.5	102.5	135.2	64.9	55.5	90.1	102.7
Final energy	[kWh/m^2]	31.2	38.9	30.5	57.6	27.7	37.0	32.6	53.2
Annual heating demand	[kWh/m^2]	8.3	23.7	13.7	42.5	8.9	23.3	11.7	39.5
Annual cooling demand	[kWh/m^2]	-7.8	0.0	-1.8	0.0	-5.3	-0.1	-7.4	0.0
Annual DHW demand	[kWh/m^2]	15.1	15.1	15.1	15.1	13.6	13.6	13.6	13.6
Heating Peak power	[kW]	20.9	26.1	12.4	27.4	76.3	76.7	85.6	73.6
Cooling Peak power	[kW]	-17.8	-4.4	-10.3	0.0	-35.1	-11.0	-45.8	-9.1
DHW Peak power	[kW]	21.3	20.5	21.3	20.6	77.2	73.4	77.3	77.5
Annual electric energy per net area	[kWh/m^2]	49.5	55.9	60.2	70.5	39.3	47.1	54.4	60.4
Electric energy for lighting	[kWh/m^2]	0.9	0.7	1.2	1.1	1.1	0.8	1.9	1.4
Electric energy for appliances	[kWh/m^2]	29.7	31.3	39.6	34.8	23.6	26.9	35.6	30.6
E-Mobility	[kWh/m^2]	-	-	-	-	-	-	-	-
Renewable energy installed capacity	[kW]	32.6	32.2	32.6	31.7	136.2	139.7	209.1	207.0
Renewable energy generation	[kWh/m^2]	61.8	48.1	40.2	41.7	46.3	41.0	45.0	46.0
Self consumed generated energy	[kWh/m^2]	34.5	27.3	27.8	19.9	21.2	24.3	27.0	27.4
Imported renewable energy	[kWh/m^2]	5.9	13.1	7.7	48.0	7.2	10.4	6.5	31.4
Imported non renewable energy	[kWh/m^2]	9.0	15.6	24.8	2.5	10.9	12.4	21.0	1.7
Exported renewable energy	[kWh/m^2]	10.2	7.7	1.2	11.4	14.5	7.5	7.8	9.6
Self sufficiency	[-]	70%	49%	46%	28%	54%	52%	50%	45%
Self consumption	[-]	56%	57%	69%	48%	46%	59%	60%	60%
IAQ- CO2	[ppm]	702	650	710	704	697	644	850	705
Thermal - % Yearly hours within indoor temperature ranges	[%]	99.3%	97.5%	100.0%	99.7%	98.8%	96.5%	98.4%	92.6%
Thermal - % Yearly hours within indoor relative humidity ranges	[%]	92.9%	96.9%	88.5%	94.0%	94.1%	97.4%	89.9%	92.3%

Figure 47. KPIs for rule-based control logic

		Low-Rise				High-Rise			
		Mediterranean	Continental	Oceanic	Sub-Artic	Mediterranean	Continental	Oceanic	Sub-Artic
Primary energy conversion factor	[-]	2.42	1.37	2.3	2.28	2.42	1.37	2.3	2.28
national %renewable in grid	[-]	0.398	0.457	0.236	0.95	0.398	0.457	0.236	0.95
Primary energy	[kWh/m^2]	71.7	67.6	103.6	134.9	64.6	55.9	88.9	100.7
Final energy	[kWh/m^2]	34.3	40.2	32.4	57.0	30.3	38.0	33.6	51.6
Annual heating demand	[kWh/m^2]	9.9	25.0	13.8	41.9	10.2	24.0	11.9	38.0
Annual cooling demand	[kWh/m^2]	-9.3	-0.1	-3.5	0.0	-6.6	-0.4	-8.2	0.0
Annual DHW demand	[kWh/m^2]	15.1	15.1	15.1	15.1	13.6	13.6	13.6	13.6
Heating Peak power	[kW]	21.0	26.0	19.5	27.5	74.6	78.3	85.2	74.1
Cooling Peak power	[kW]	-22.1	-4.0	-18.2	-2.5	-52.6	-19.7	-55.0	-11.2
DHW Peak power	[kW]	21.4	20.6	20.6	20.6	77.5	76.4	77.5	77.5
Annual electric energy per net area	[kWh/m^2]	51.1	57.1	61.0	71.5	40.3	47.8	54.6	60.1
Electric energy for lighting	[kWh/m^2]	0.9	0.7	1.2	1.1	1.1	0.8	1.9	1.4
Electric energy for appliances	[kWh/m^2]	29.7	31.3	39.6	34.8	23.6	26.9	35.6	30.6
E-Mobility	[kWh/m^2]	-	-	-	-	-	-	-	-
Renewable energy installed capacity	[kW]	32.6	32.2	32.6	31.7	136.2	139.7	209.1	207.0
Renewable energy generation	[kWh/m^2]	61.8	48.1	40.2	41.7	46.3	41.0	45.0	46.0
Self consumed generated energy	[kWh/m^2]	36.6	28.8	28.3	21.9	23.2	25.9	28.2	28.3
Imported renewable energy	[kWh/m^2]	5.8	12.9	7.7	47.0	6.8	10.0	6.2	30.2
Imported non renewable energy	[kWh/m^2]	8.7	15.4	25.0	2.5	10.3	11.9	20.1	1.6
Exported renewable energy	[kWh/m^2]	8.2	6.2	0.8	9.3	12.8	6.1	6.6	8.8
Self sufficiency	[-]	72%	50%	46%	31%	58%	54%	52%	47%
Self consumption	[-]	59%	60%	70%	53%	50%	63%	63%	62%
IAQ- CO2	[ppm]	702	650	710	704	697	644	851	705
Thermal - % Yearly hours within indoor temperature ranges	[%]	97.3%	95.0%	98.0%	92.7%	98.6%	94.5%	98.0%	86.6%
Thermal - % Yearly hours within indoor relative humidity ranges	[%]	93.1%	97.0%	88.1%	93.0%	93.8%	97.2%	89.4%	91.5%

Figure 48. KPIs for advanced control logic

Figure 47 and Figure 48 report some key performance indicators (KPIs) defined in deliverable D4.1 [3].

It is possible to notice that both control strategies allow to maintain a satisfactory thermal comfort and environmental air quality. The main difference between the two strategies is when the energy system is active and when not. The rule-based control strategy minimizes the electrical consumption of the system. However, because this energy is often needed when there is no PV production, it is necessary to withdrawn part of this energy from the grid. Moreover, a consistent part of the energy produced by the PV is ether stored in the battery of sent to the grid. The advanced control strategy consumes more energy. Nevertheless, this energy is mostly covered by the PV production. Thus, the electricity withdrawn from the grid is lower.

In principle it might be possible to reach higher self-consumption and self-sufficiency by increasing the size of the electrical energy storage (battery). However, this would mean a higher investment cost and longer pay-back periods. Moreover, when the electricity is sent and then withdrawn from the battery there are losses due to the inverters and the rectifiers that reduce the efficiency of the system. Therefore, it is better to exploit the electricity produced by the PV system directly.

4 Control strategies at neighbourhood scale (top-down approach)

The publication of the EU Clean Energy for All Europeans Package [6] and the Renewable Energy Directive II [7] emphasizes the key role of citizens to collectively self-produce their energy requirement from renewable sources and develop a local energy market.

Photovoltaic (PV) systems will play a key role in this framework, as they enable for the creation of “Renewable Energy Communities” (RECs). The REC is a legal entity aggregating passive consumers and PV owners to enable their participation in the electricity market, lower the electricity costs, and decrease the payback period for the PV investment by increasing the quota of renewables. Generally, the higher the consumption patterns heterogeneity, the higher the energy benefits of joining a REC.

Two key elements support the technical implementation of energy sharing: the existence of a smart-metering infrastructure based on information-communication technologies and the definition of suitable control strategies for the battery energy storage systems (BESS). The first allows gathering production and consumption data and thus interact with the BESS, while the second is responsible for the energy management process.

The definition and implementation of renewable energy community and the related regulations vary country by country. For example, in Italy, there is a distinction between “collective self-consumption” and renewable energy community. The first one is dedicated to the single building multi-family house, while the second one considers the energy shared among more than one building, as reported in Figure 49. Moreover, currently, a REC can be born in Italy regarding the geographical proximity and belonging to the same secondary substation. However, this definition is currently being revised and favoring an energy community made up of virtual nodes not belonging to the same secondary cabin but extending the domain to the primary substation.

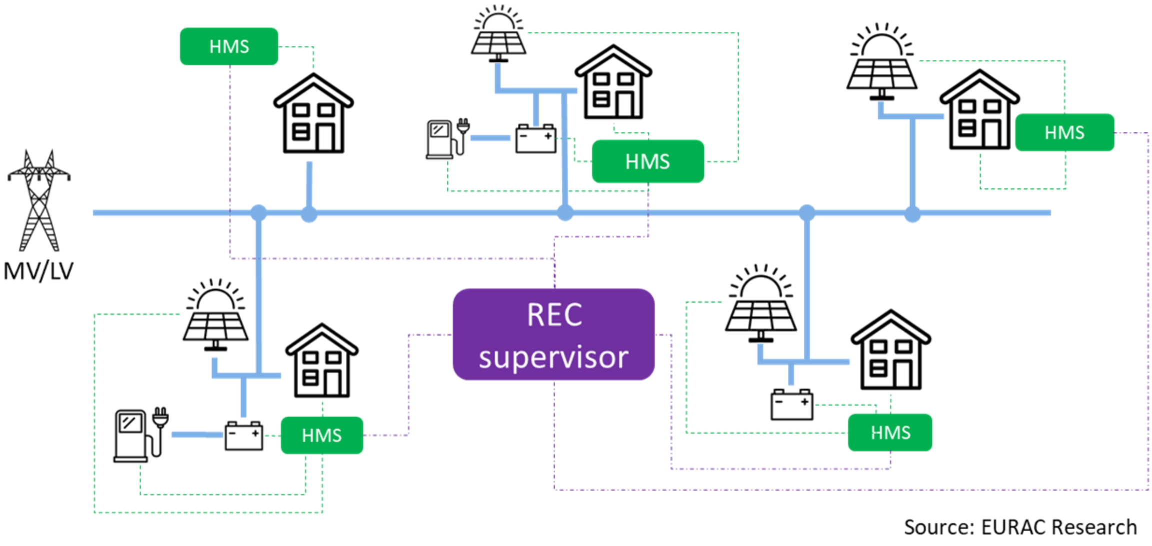


Figure 49. Scheme of a renewable energy community (REC). The REC is a legal entity that aggregates passive consumers and *prosumers* who can be equipped with photovoltaics and battery electrical storage systems.

The purposes of the renewable energy community are various and go beyond the maximization of renewable share, including social, economic, and environmental impact. However, focusing on this aspect, the REC aims to use locally produced renewable energy and bring possible economic advantages at the community and individual level from the minimization of the energy from the grid and in compatibility with any incentives provided for such a logic of sharing local resources. A third aspect envisaged touches on environmental issues, probing the environmental impact of a better use of locally available renewable energy resources and involving several actors in the same area.

In the energy management of an energy community, two distinct groups of actors stand out. On the one hand, the individual users are involved; on the other, a third entity is responsible for coordinating or managing energy flows within the community. This entity referred to here as the “REC supervisor” carries out a virtual balance of the consumption of the community as a whole by summing up the information derived from the various users. According to an internally defined algorithm, it is possible to act on the degrees of freedom within the system formed by the community. Coordination can take place in a distributed or centralized manner. The supervisor can process a production or consumption signal intended for the individual prosumer's storage system. As introduced, the objective of an energy community is to seek greater consumption of locally available energy resources. Therefore, the control task is to try to zero the balance resulting from the sum of the individual contributions of the nodes involved. On the practical side, this means trying to store the surplus energy produced within the storage systems available in the community, even if not directly part of the node that generated the renewable production. Similarly, where the community requires a power greater than that available, the control requires the intervention of the available storage systems to reduce the energy withdrawn from the grid by the entire community. The individual node in the community operates according to the external control signal from the supervisor. When this signal is assigned, the single user operates its systems in coordination with the external supervisor. Conversely, when the external forcing signal is not present, each individual user reverts to operating according to the locally calculated logic based on the balance of local production and consumption.

Several factors may contribute to the variation of performance and effectiveness of community aggregation of a group of N users. An attempt is made below to suggest some qualitative factors that may condition the energy performance of an energy community.

- Heterogeneity of users included in the community. This includes both the variability in terms of technological equipment installed (PV, BESS, electric mobility) and consumption characteristics. The latter component can be expanded in terms of total consumption (quantitative indication of user consumption) and in terms of correlation of consumption behavior. A greater heterogeneity between users' habits and consumption patterns can increase the benefits of introducing a community logic. On the other hand, users who concentrate their higher consumption in the same time slots, or with the same habits, can reduce the potential benefits introduced by the community logic.
- The geographical proximity of the community's users reduces the diversity found in climatic data, which is essential for PV production and the consumption pattern induced by external weather and temperatures (such as heating and cooling). The production diversity of individual users, all climatic conditions being equal, remains linked to the characteristics of each PV plant. Different plants may differ significantly regarding positioning (exposure to the sun, inclination, shadows from other structures or obstacles, etc.).
- The final component that can affect the performance of the community is the implemented supervisor algorithm that practically governs and coordinates the flexibility of energy flows available within the community.

A final observation concerns the economic benefits that can derive from being part of such a community. While greater use of local energy resources reduces the energy imported from the grid and related costs, incentives due to national legislation can introduce an additional source of income. These benefits are valid at the community level and require the adoption of an adequate criterion to remunerate each member of the community for their participation.

4.1 Control-logics at the community level

In this chapter, we introduce two rule-based control strategies, published in [8] and modified in [9], to perform energy sharing at the community level by properly managing the energy storage systems available within the REC. The first one, called *Peer-to-Grid (P2G)*, is a decentralized control where the individual node operates according to a logic elaborated based on local production and consumption variation (Figure 50).

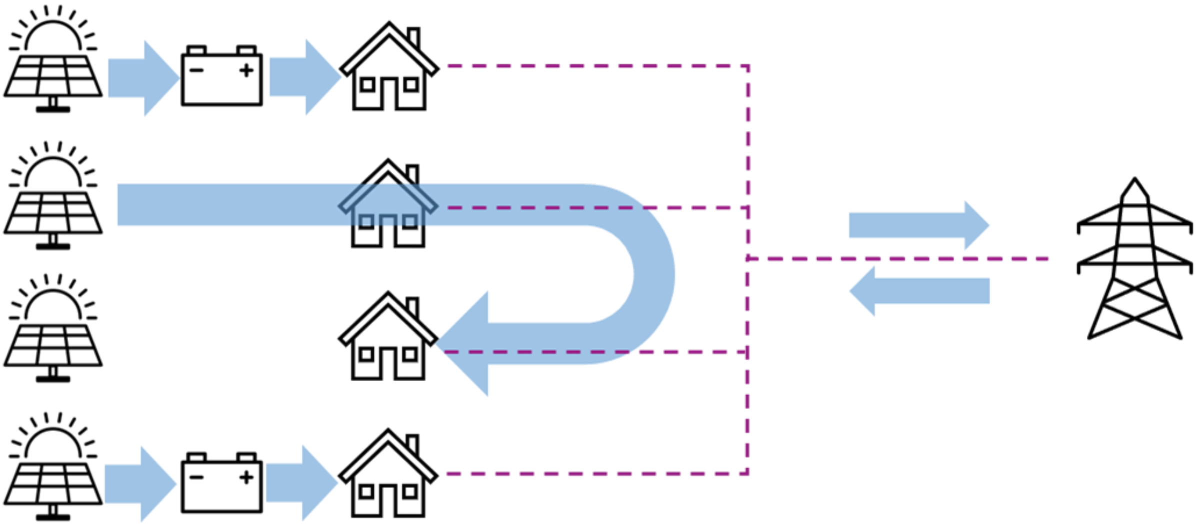


Figure 50. Peer-to-grid control logics

This case sees a community of heterogeneous users operating locally and trying to manage their energy resources. The introduction into a community means that the overproduction of one user can be exploited instantaneously by another community member. No active coordination is present while sharing overproduced energy remains possible. The excess is exported to the grid; conversely, each user takes as much as the load-production balance requires from the grid.

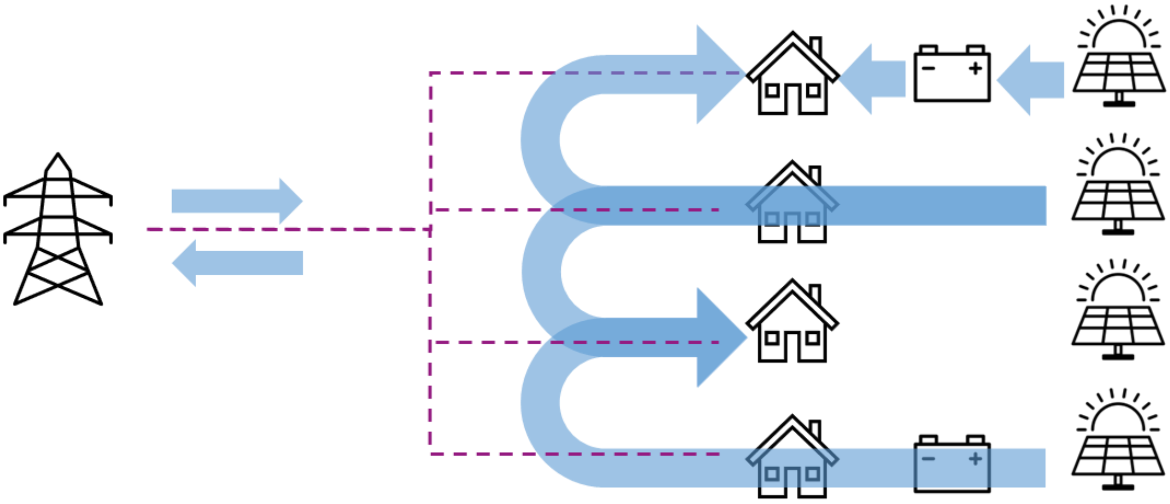


Figure 51. Simplified representation of Peer-to-Peer control strategy.

The second logic, called *Peer-to-Peer* (P2P Figure 51), involves introducing coordination in sharing available energy resources. The REC supervisor (Figure 49) coordinates in a centralized manner the exploitation of energy flexibility within the community. This third-party actor actively operates by seeking greater exploitation of locally produced and stored energy resources. Any degree of freedom present at the individual node level, i.e. the storage system or any available schedulable loads, is then managed based on an external signal processed centrally based on an algorithm implemented in the supervisor (an example in Figure 52). This paradigm of community governance allows, for instance, the use of a storage system to retain locally the energy produced by the user and other users in the same community. The same approach can be taken to retain more of the overproduction and cover loads of users in the community if PV generation is insufficient.

The two introduced algorithms differ in the priority given to the needs of the local node. In the P2G case, priority is given to the production and consumption of the individual node, which, when equipped with a storage system, can either absorb or fully cover its overproduction or consumption. In addition to this direct contribution, the single node can receive a share of the consumption or overproduction of the other community members that may have exhausted their energy flexibility resources. The second algorithm, the P2P approach, does not prioritize the single node requirements and operates by allocating overproduction and consumption exclusively on the base of the status of the storage systems present within the community

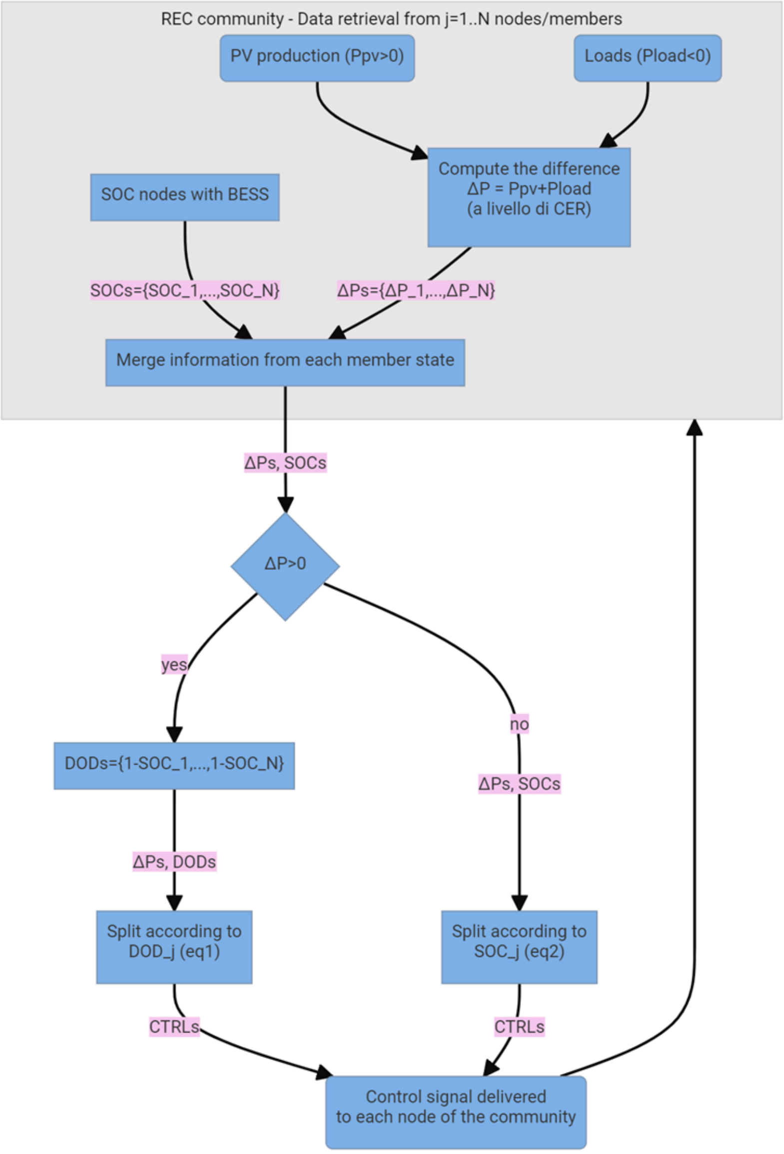


Figure 52. Flow-chart representing an example of control logic developed according to the peer-to-peer control paradigm. The composition of $P_{\Delta,tot}(t)$ determines the difference between logic P2G and P2P and the actual prioritization at the local level in prosumer nodes.

Figure 52 reports an example of the centralized algorithm. It operates with a rule-based logic knowing the instantaneous production and consumption of the individual nodes of the community and the state of charge (SOC) of any storage system installed. By processing these two pieces of information, a control signal in power is calculated and assigned to each community member that tries to modify its consumption (for example exploiting the flexibility brought from the storage system) to track the indication of the supervisor.

The production excess or the required power is distributed among the grid members. The power to be allocated is distributed by weighing the different contributions based on the depth of discharge (DoD) or state of charge of the individual storage system (depending on whether it is excess power produced (eq 1) or power consumed (eq 2)).

$$P_{BESS,discharge,j}(t) = P_{\Delta,tot}(t) \cdot \frac{DoD_j(t-\Delta t)}{\sum_{j=1}^{N} DoD_j(t-\Delta t)} \tag{1}$$

$$P_{BESS,charge,j}(t) = P_{\Delta,tot}(t) \cdot \frac{SOC_j(t-\Delta t)}{\sum_{j=1}^{N} SOC_j(t-\Delta t)} \tag{2}$$

Where $P_{\Delta,tot}(t)$ is the community-level power budget valid for the algorithm P2P

$$P_{\Delta,tot}(t) = \sum_{j=1}^{N} \left(P_{load}(t) - P_{PV}(t)\right)_j \tag{3}$$

and N is the total number of nodes in the community. For the counterpart with P2G and priority to local consumption, only the power of nodes without batteries is added, while nodes with storage systems are assigned the total of their overproduction or consumption plus a share (according to equations 1 and 2) from nodes without storage systems.

5 Conclusion

The analysis reported in Par. 3.3 highlighted some features of the control logics that can be summarized to provide a better insight on the building's management.

The rule-based control logic that harmonizes the different technologies implemented in the energy system and the building, proved to be effective in guaranteeing sufficient levels of thermal comfort and environmental air quality. This control strategy aims at minimizing the overall electrical energy consumption of the building. However, it does not consider the presence of the PV system and it is not meant to match the loads with the production. Thus, both self-sufficiency and self-consumption are not optimized. The advanced control strategy aims at reducing the electrical energy withdrawn from the grid and maximizing both self-sufficiency and self-consumption. Generally, the advanced logic increases the total electric energy consumption but reduces the electrical energy withdrawn from the grid.

In order to enhance the flexibility of the thermal energy storage for domestic hot water it is necessary to triple the size defined in the technical standards. This allows to reduce the number of charging and discharging cycles within a day. If this feature is coupled with a proper control strategy it is possible to shift the thermal load of the heat pump. With the rule-based control strategy the thermal energy storage is charged during the first hours of the morning, when there is no electrical energy production, and the battery is usually fully discharged. This means that the energy needed to run the heat pump should be withdrawn from the grid. The increase of the setpoint of the thermal energy storage for domestic hot water during the central part of the day shifts the charging cycles in the central part of the day, when the outdoor temperature is higher and there is the peak of PV production. Nevertheless, the increase of performance due to the temperature increase on the evaporator does not cover the decrease of performance due to the increase of temperature at the condenser. Therefore, the COP of the heat pump decreases and the electrical energy consumption increases. However, because the load is shifted in the central part of the day, it is possible to exploit the production of the PV system. In order to reduce the electrical energy withdrawn from the grid, the setpoint of the thermal energy storage should be increased only in the days in which the predicted PV production is higher than the predicted electrical energy consumption. This is always the case during the warmer months while it is less probable during winter, especially for colder climates.

A similar reasoning is also valid for space heating. With the rule-based control strategy the thermal demand of the building is concentrated during the colder period of the day when there is no PV production. Consequently, the heat pump works with less favorable conditions. It is possible to shift the space heating demand by acting on the space heating setpoint in the dwellings. The night setback allows the shift of the night load toward the morning hours. However, both the total electrical energy consumption and the electrical energy withdrawn from the grid are not reduced. The increase of the space heating setpoint during the central part of the day increases the COP of the heat pump because the temperature at the evaporator gets higher and the temperature at the condensed gets lower as the distribution setpoint is lower (climatic curve). Therefore, even if the thermal energy produced by the heat pump increases, the electrical consumption of the heat pump is similar. The electricity withdrawn from the grid can be either higher or lower, depending on the PV production. During the cold heating season the thermal load is high, so it makes sense to increase the space heating setpoint when the predicted daily PV production is at least half of the predicted daily consumption. This reduces the electrical energy withdrawn from the grid. During the mild heating season, the same reasoning is valid. However, as the thermal demand of the building is lower, it is better to increase the space heating setpoint by 1 K to avoid overheating.

For space cooling the reasoning is different because already with the rule-based control the loads are concentrated in the afternoon when the PV production is high. The shift of the space cooling load toward the first part of day increases the EER of the heat pump due to the lower temperature at the source side of the heat pump. However, this increases the thermal discomfort in the central part of the day and decreases the self-consumption of the energy system. The decrease of the space cooling setpoint in the central part of the day decreases the EER of the heat pump and increases the thermal demand of the building as well as the electrical energy consumed by the ceiling fans.

During the mild cooling season, the self-sufficiency of the system is already high with the simple rule-based control. Only in few cases the PV does not cover the load (days in which there is a lower PV production). Thus, it makes no sense to decrease the space cooling setpoint during this period of the year. From an energetic point of view, it is more effective to achieve the thermal comfort with the activation of the ceiling fans. During the hot cooling season, the decrease of the space cooling setpoint during the afternoon has a positive impact only when the predicted PV production is higher than the forecasted consumption of the building. However, it is sufficient to reduce the setpoint by 1 K to lower the electrical energy withdrawn from the grid.

The advanced control logics demonstrates that it is possible to shift the loads by acting on few setpoint temperatures. The change of the setpoint to shift the loads usually increases the total electrical consumption. The load shifts have a positive impact on the system performance only when the additional consumption is covered by the PV system. In winter the self-consumption is close to 100%, meaning that the only way to further reduce the electricity withdrawn from the grid is to increase the size of the PV system. As the roof and façades of the buildings are completely exploited, the additional PV should be installed somewhere else, which might be not feasible. During spring and autumn, the thermal load is low, and it could be possible to avoid any withdrawal from the grid by increasing the size of the battery by 20%. In summer a positive balance is reached. However, during some days in which there is a lower PV production there is still the need to withdraw electricity from the grid.

When dealing with air-to-water heat pump it is important to select the correct position of the external unit. A correct positioning of the external unit can increase the COP of the heat pump, thus, decrease the electrical energy consumption. If the heat pump is exposed to the sun the temperature at the evaporator is higher than the outdoor air temperature. Moreover, this helps in avoiding the frosting of the units. Nevertheless, this would also decrease the EER during the summer operation. These hyperlocal effects must be considered case by case during the design phase.

In high efficiency buildings an important role is played by the fixed electrical loads due to appliances and lighting. Appliances are particularly crucial because their consumption are more than half of the total electrical consumption. For this reason, a sophisticated control strategy is not always sufficient to reach a positive balance throughout the year. Energy efficient appliances and an optimal selection of their working period are crucial to reach the positive energy balance. For this reason, the building's users should be aware of when it is convenient to use the appliances and when it is not the case.

The rule-base control represents the starting point for the definition of the house management system (HMS) developed by AdvanticSys in the framework of H2020 Cultural-E project. The control will be readapted to be compatible with the real buildings under construction as demo cases. The advanced control strategies that include the weather forecast and the prediction models will be developed in the cloud-based house management system.

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