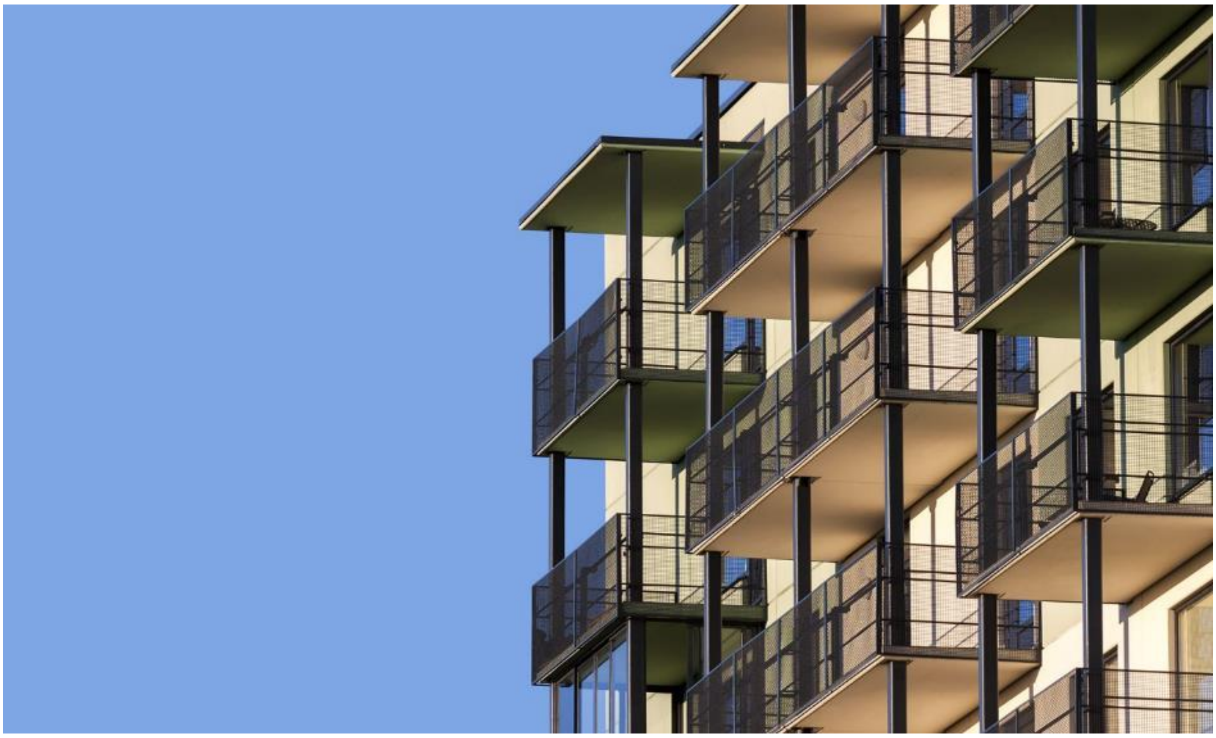
D4.5 – Retrofit protocols



Standardised approaches and products for the systemic retrofit of residential BUILDings, focusing on HEATing and cooling consumption attenuations

BuildHeat

Project Title: Standardised approaches and products for the systemic retrofit of residential BUILDings, focusing on HEATing and cooling consumption attenuations.

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1 Introduction

In Europe, more than 80% of existing buildings was built before 1990, year when norms on energy efficiency started to be implemented [1]. This means that the majority of European residential building stock is poorly efficient and has a big potential of improvement through renovation. The actual renovation rate through Europe is around 1-1.5%, quite small with respect to the available buildings. Some of the reasons of this low renovation rate are: i) high installation costs; ii) lack of knowledge from the decision maker on the optimal solution for the specific case; iii) low acceptance of works from the tenants and apartments owners; iv) lack of awareness of the benefit that renovation works bring to the building owners and tenants.

European countries that have more than 50% of their residential floor area in multifamily houses (MFHs) are Latvia (74%), Italy (70%), Estonia (70%), and Spain (67%). Despite this, MFHs are often thought to be more cost-effective targets for retrofit because of the lower cost per m² of the intervention, sharing of fixed costs, management of the intervention by an external person and not by tenants/dwellings owners. For this reason, the following work is focused on intervention aimed to MFHs.

In this context, this document aims at reporting some renovation solutions involving envelope, HVAC system and renewable energy, applied to different residential buildings typologies located in different countries through Europe. For each solution, performance in terms of energy savings, use of renewables, environmental impact and operative costs is analysed.

Due to the differences between the proposed solutions, building typologies and climates, an analysis on the impact of each intervention is reported per analysed case. Finally, some conclusions will summarize and guide on the pros and cons of the different intervention, depending on the climate, building typology and costs.

2 Methodology

2.1 Retrofit packages definition and adopted approach

The approach adopted in this study analyses the influence that interventions on an existing building have on energy, environmental and economic aspects.

The developed methodology consists on the definition of reference buildings located through Europe which retrofit packages are applied to. The retrofit packages include envelope insulation, windows replacement, heating and cooling generation efficiency improvement and adoption of renewable energy sources (see Figure 1).

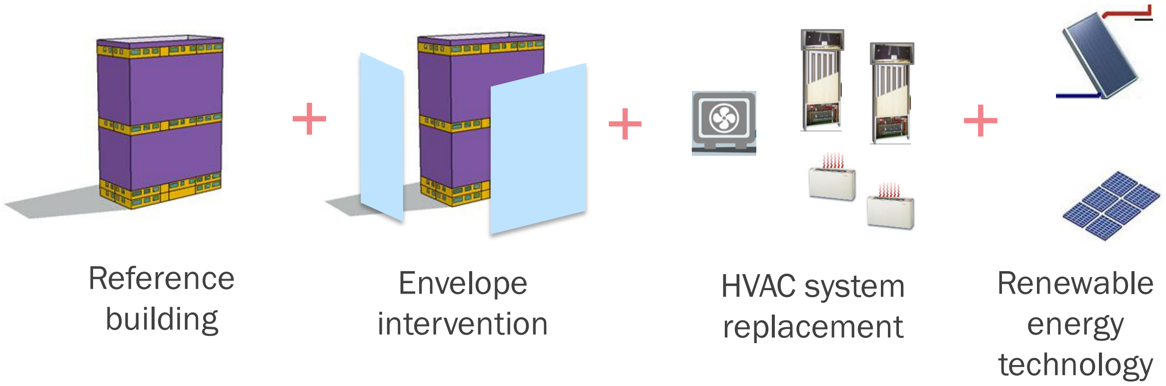


Figure 1 – Methodology for the study of retrofit protocols

The reference buildings are multi-family houses for the reasons above presented, although they represent more than half of the heated area only in some European countries [1]. Since 80% of them are built before 1990, there is a big potential of decarbonization of the residential sector if retrofit solutions are applied to these building typologies. The considered construction period is the 1980-1990, this implies that thermal characteristics of the building before renovation are in line with those of that period for each specific location.

For taking into account different building shapes and therefore heating demands while maintaining the same external surface transmittance, four building typologies are used with different surface over volume ratio (S/V). The four reference building typologies are: low rise building, high rise building, small multi-family house and large multi-family house. Details on the building typologies are reported in the following paragraphs.

The demand variability and external conditions are taken into consideration by running dynamic simulations in four different climates through Europe: Oceanic for a cold-mild northern climate, Continental as European cold climate, Southern Dry and Mediterranean for warm climates dry and humid. Weather analysis on the four location is reported in section 2.2.

The starting point of the methodology is the definition of reference buildings assumed to be built in the period 1980-1990, therefore with the average thermal characteristics referred to that period. To these, intervention on the envelope are applied, aimed at reducing the building demands by following the national requirements of thermal transmittance in renovation works. A focus on the reference building typologies is reported in sections 3.1, 3.2, 3.3, 3.4.

In order to improve energy efficiency of the existing buildings and contribute to the reduction of CO_2 emissions, the approach foresees the replacement of the existing HVAC system with a more efficient one. In some cases, the configuration of the system is connected to the building typology due to some technological constraints, while in others, different dwellings sizes and exposures can cover an extended number of cases. A detailed description of the analysed HVAC systems is reported in section 3.5, 3.6 and 3.7.

The analysis of the possible renovation interventions considers renewable energy technologies for additionally reducing the use of energy. Depending on the building typology and available external surface (roof or external walls oriented to South, East or West), each renovation solution could use, at dwelling or building level, photovoltaic, solar thermal system or both.

The so individuated reference cases with different retrofit packages applied are run in TRNSYS, a dynamic environment [2], in four climatic conditions for assessing the energy behaviour under different working conditions (see Figure 2).

For each Retrofit Solution (RS) package composed by intervention on the envelope, HVAC system replacement and use of renewable energy, performance indicators on energy, environment and economy have been studied and collected in an online available database [3]. In the following paragraphs, the used KPIs are explained.

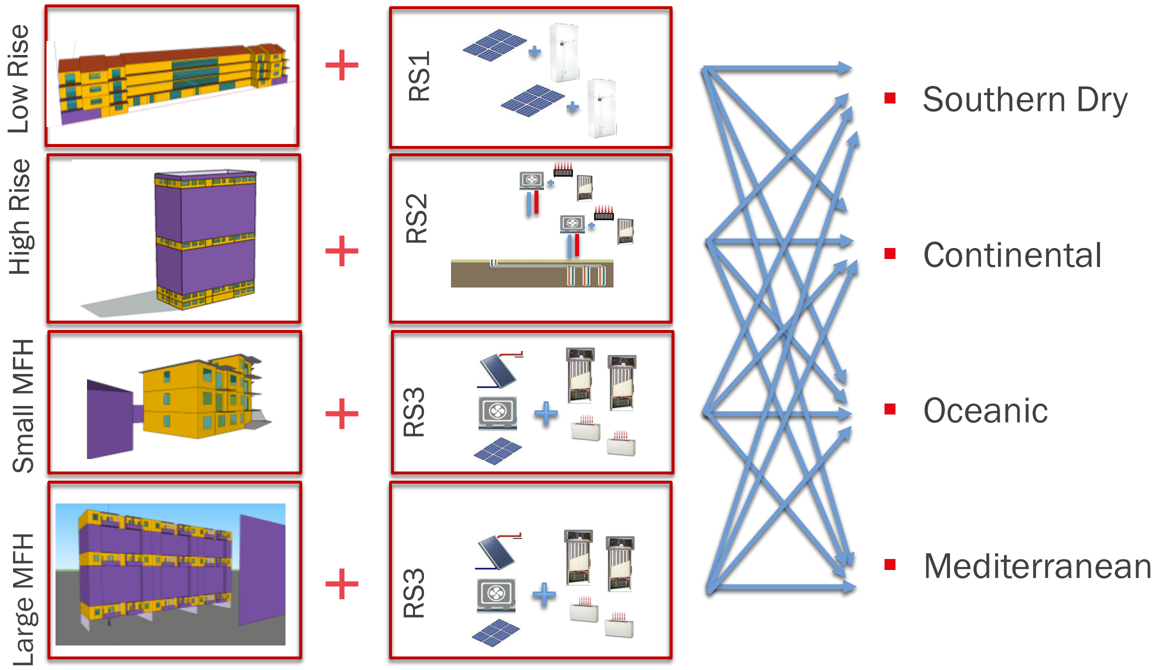


Figure 2 – Combination of reference buildings and retrofit packages in different climatic conditions.

2.2 Climate variants

Energy performance of reference buildings with retrofit packages are assessed for four different climate conditions as representative of the whole Europe. The representative climates are used for defining the building thermal characteristics before and after renovation and weather conditions that influence the renewable energy production. A country is representative of the climatic zone and is taken into consideration for the definition of the building transmittance characteristics and requirements to be fulfilled, while a city is used for the external weather file. Table 1 summarizes the four climates with the associated reference countries and cities. The fourth column of the table reports the Heating Degree Days (HDD) calculated on 18°C basis for the last 3 years (2017-2019). To be noted as the four climates differ of around 500 HDD each being therefore representative of a large part of the European territory. The table also provides the average yearly temperature, which characterizes the climate and the ground temperature.

Table 1 – Reference climatic conditions and heating degree days

Reference climate	Country	City	Heating degree days [5]	Average temperature [°C]
Continental	Germany	Stuttgart	2902	9
Oceanic	United Kingdom	London	2452	12
Southern Dry	Spain	Madrid	1993	14
Mediterranean	Italy	Rome	1400	16

Figure 3 (left) reports on the external temperature distribution along the year for the four reference climates. The Continental climate results to be the coldest during the winter period, while the Oceanic climate presents lower temperatures during summertime. Southern Dry and Oceanic climates have similar minimum temperatures, but Southern Dry shows the highest temperature between the four. Finally, the Mediterranean climate results to have a mild winter and a warm/hot summer.

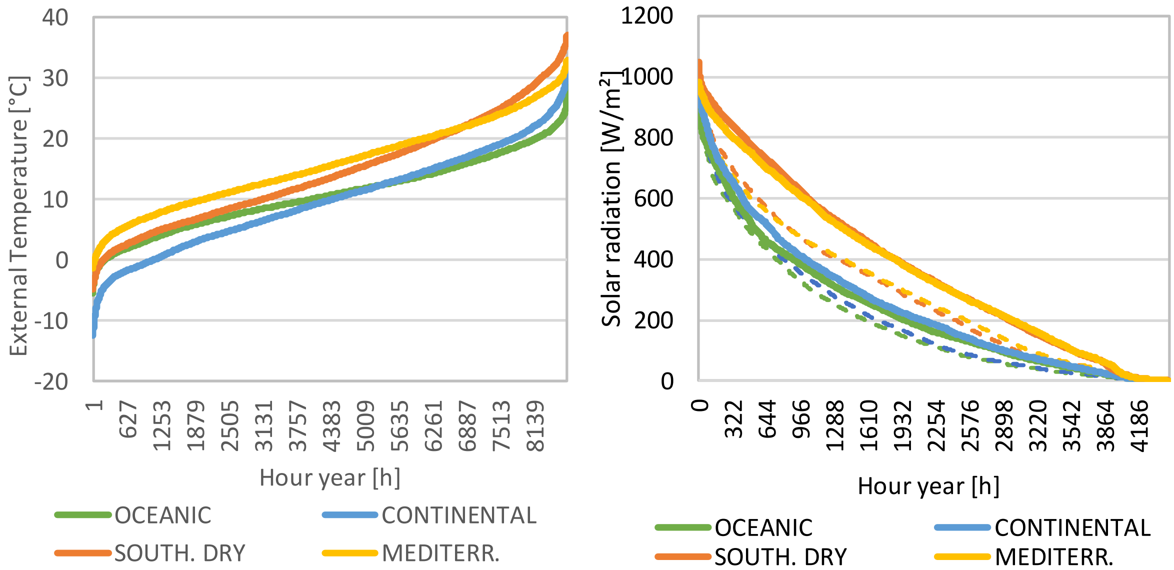


Figure 3 – External temperature distribution (left) and solar radiation on the horizontal (solid line) and on a south oriented surface (dashed line) for the four reference climates (right)

Weather files are obtained from Meteonorm v6 for the four reference cities [4]. Analysing the solar radiation, Continental and Oceanic climates have similar solar radiation both on the horizontal and on the south faced surface. Similarly, Mediterranean and Southern Dry climates show very similar solar radiation trends throughout the year and higher than the other two climates (Figure 3 right).

Table 2 to Table 5 summarize monthly values for each climate of maximum solar radiation on the horizontal, and minimum, average and maximum external temperature.

Table 2 – External weather conditions for building simulations in the Oceanic climate

MONTH		Max Solar Radiation	Average external temperature	Min ext. temperature	Max. ext. temperature	MONTH	Max Solar Radiation	Average external temperature	Min ext. temperature	Max. ext. temperature
		[W/m²]	[°C]	[°C]	[°C]		[W/m²]	[°C]	[°C]	[°C]
JAN		330	5.4	-5.5	13.2	**JUL**	898	17.4	7.7	28.8
FEB		464	5.2	-4.0	14.1	**AUG**	858	17.3	8.2	26.2
MAR		670	6.8	-2.9	16.6	**SEP**	749	14.6	5.7	24.3
APR		767	9.4	-0.7	18.7	**OCT**	572	11.5	2.0	20.2
MAY		898	12.9	3.1	23.8	**NOV**	437	8.0	-0.3	16.1
JUN		952	15.7	5.7	27.4	**DEC**	258	5.2	-3.2	13.9

Table 3 - External weather conditions for building simulations in the Continental climate

MONTH	Max Solar Radiation	Average external temperature	Min ext. temperature	Max. ext. temperature	MONTH	Max Solar Radiation	Average external temperature	Min ext. temperature	Max. ext. temperature
	[W/m²]	[°C]	[°C]	[°C]		[W/m²]	[°C]	[°C]	[°C]
JAN	415	0.8	-12.5	12.5	**JUL**	908	18.9	8.3	32.4
FEB	559	2.3	-9.3	14.1	**AUG**	947	18.6	9.3	31.5
MAR	844	5.5	-5.3	19.8	**SEP**	801	14.1	4.1	26.7
APR	875	9.8	-3.2	22.1	**OCT**	502	10.2	0.1	20.8
MAY	965	14.4	3.0	28.7	**NOV**	463	5.1	-2.9	16.5
JUN	1014	17.6	5.5	30.4	**DEC**	320	1.6	-7.9	11.4

Table 4 - External weather conditions for building simulations in the Southern Dry climate

MONTH	Max Solar Radiation	Average external temperature	Min ext. temperature	Max. ext. temperature	MONTH	Max Solar Radiation	Average external temperature	Min ext. temperature	Max. ext. temperature
	[W/m^2]	[°C]				[W/m^2]	[°C]	[°C]	[°C]
JAN	548	5.2	-4.2	16.3	**JUL**	1045	25.7	13.0	37.2
FEB	675	6.7	-3.3	17.6	**AUG**	980	24.9	12.4	37.1
MAR	915	10.3	-1.2	22.9	**SEP**	887	20.0	8.8	32.4
APR	1049	12.2	1.6	24.4	**OCT**	742	14.8	5.1	25.8
MAY	1014	17.0	5.2	32.0	**NOV**	627	8.5	-1.2	21.0
JUN	1014	22.9	10.6	36.7	**DEC**	458	5.5	-4.9	16.9

Table 5 - External weather conditions for building simulations in the Mediterranean climate

MONTH	Max Solar Radiation	Average external temperature	Min ext. temperature	Max. ext. temperature	MONTH	Max Solar Radiation	Average external temperature	Min ext. temperature	Max. ext. temperature
	[W/m^2]	[°C]	[°C]	[°C]		[W/m^2]	[°C]	[°C]	[°C]
JAN	504	7.8	-1.4	17.4	**JUL**	984	24.3	15.5	33.1
FEB	593	8.3	0.2	18.1	**AUG**	927	24.6	16.4	32.9
MAR	845	11.0	1.9	20.6	**SEP**	843	20.4	11.3	30.1
APR	877	13.5	5.1	23.2	**OCT**	735	17.3	8.2	25.7
MAY	982	18.4	9.0	29.0	**NOV**	511	12.7	2.8	23.4
JUN	977	21.8	12.0	31.9	**DEC**	425	9.3	-0.3	18.5

2.3 Key performance indicators – KPIs

For assessing the performance of a retrofit solution, it is needed to adopt Key Performance Indicators that uniquely evaluate the building and HVAC system behavior. In line with this, relevant indicators used for defining energy, economic and environment performance of the retrofit packages are presented.

2.3.1 Energy performance indicators

Energy performance indicators quantify energy required by the building for maintaining the comfort conditions of 20°C during wintertime and 25°C during summertime. For considering the same boundary conditions between different climates, the comfort temperature has been assumed during the 24 hours. Definitions of the used Energy KPIs are reported in the following.

- Energy demand - ED

  Energy Demand denotes the energy required for maintaining the comfort temperature along the year for space heating, space cooling or Domestic Hot Water (DHW) need. During wintertime for space heating, this energy is positive, meaning that it is added to the thermal zone for maintaining the set point of 20°C, while during summertime for space cooling, energy is extracted by the zone for maintaining the set point of 25°C. DHW is supposed to be supplied at 45°C. In the following and in the database, this quantity is indicated in terms of energy over unit of heated area, that is $kWh/m^2 \cdot y$.

- Final energy - FE

  Final energy represents the energy used for covering the building energy demands and depends on the device. In case of gas boiler, final energy is the quantity of energy generated by natural gas through combustion. For electric resistances, heat pumps, pumps, fans and split units, final energy refers to the quantity of used electricity.

- Seasonal Coefficient of Performance, Seasonal Energy Efficiency Ratio (SCOP/SEER), boiler efficiency (η)

  The efficiency of a generation device – gas boiler, heat pump, electric resistance or split unit – is calculated through the year and an average of the hourly values is reported. For each generation device, the seasonal efficiency is calculated as the ratio between thermal energy produced by the device over the consumed energy:

$$SCOP, SEER, \eta = \sum_{year} \frac{Produced\ thermal\ energy}{Consumed\ energy}$$

  The control volume this quantity refers to is the device itself as η, SCOP, SEER represents the efficiency of the generation device under working conditions (see Figure 4).

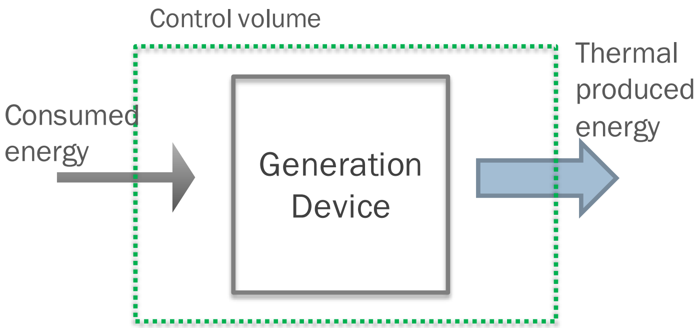


Figure 4 – Control volume for the definition of boiler efficiency, SCOP, SEER

- Seasonal Performance Factor

  The indicator that represents the efficiency of the whole system is the Seasonal Performance Factor defined as the ratio between energy demand and all electricity consumption used for producing that energy (Figure 5). Differently from the SCOP/SEER, this indicator refers to the useful energy effectively used by the building net of system thermal losses and to all electricity consumption, included auxiliaries and distribution devices (i.e. fan coils).

$$SPF_{el} = \frac{Energy\ demand}{Electric\ consumption}$$

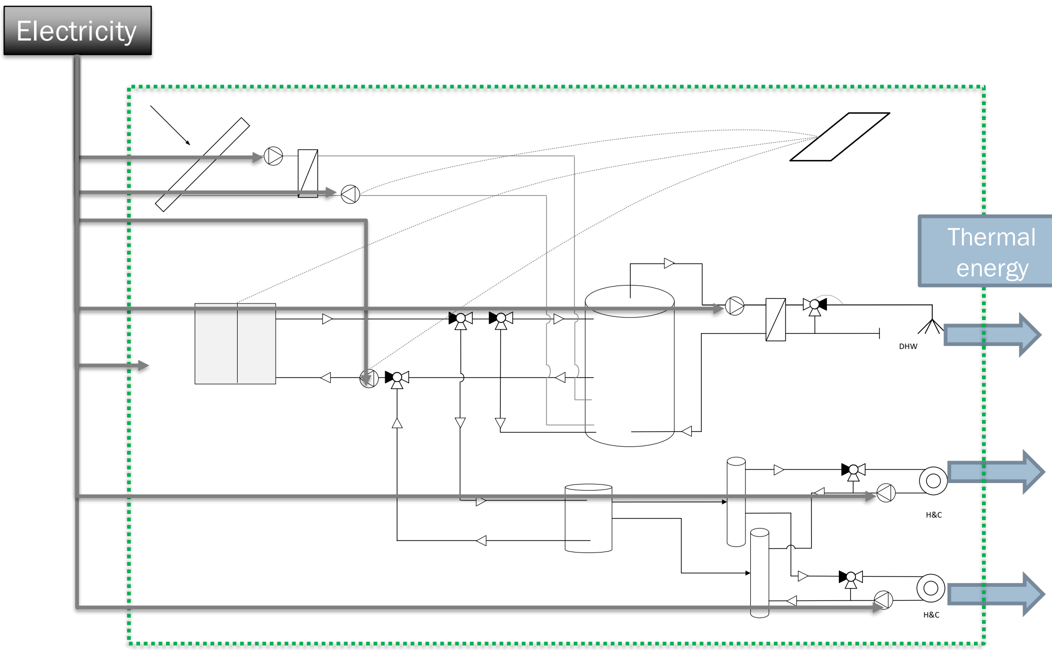


Figure 5 – Control volume for the calculation of the SPF

Due to the definition, SPF can be referred to one energy source only. In the following, SPF refers to electricity. This indicator can be calculated for all the building uses or for each use as space heating, space cooling, DHW.

- Solar contribution

  In the systems considered in the following, the presence of a solar thermal system can contribute to space heating or DHW production by providing part of the required energy with energy harvested through solar collectors. This contribution is accounted in percentage as it represents the share of space heating (SH) or DHW covered by solar energy.

$$SC = \frac{Solar\ thermal\ energy\ for\ SH\ or\ DHW}{Total\ thermal\ energy\ for\ SH\ or\ DHW}$$

- PV use

  The contribution of a PV system to the reduction of a system electric consumption is accounted in terms of PV self-consumption. In particular, in the following paragraphs these definitions are used:

  PV self-use fraction is the percentage of electric energy produced by PV and directly used by the HVAC system.

$$PV_{use} = {W_{\mathrm{PV,used}}}/{W_{consumption}}$$

where $W_{\mathrm{PV,used}}$ is the self-consumed PV energy and $W_{consumption}$ is the total electricity consumed. This quantity is computed hourly and takes into account the simultaneity between PV production and electricity consumption

PV self-consumption is energy produced by the PV system and used by the devices that at the same time are consuming electricity; this is an hourly-based calculation;

$$PV_{self} = {W_{\mathrm{PV,used}}}/{W_{produced}}$$

where $W_{\mathrm{PV,used}}$ is the self-consumed PV energy and $W_{produced}$ is the total electricity produced by PV. This quantity is computed hourly and takes into account the simultaneity between PV production and electricity consumption

PV production represents the electricity produced by the PV system and then used by the system or sent to the grid.

Electricity to the grid is the surplus energy produced by the PV system, which is fed into the grid.

2.3.2 Environment performance indicators

- Primary energy

Primary Energy consumption is an indicator that allows a comparison between different energy sources and takes into account energy consumed for producing electricity or gas. Primary Energy multiplies Final Energy for a Primary Energy Factor that quantifies the non-renewable primary energy used to provide the final energy, including the energy used for construction of the electric grid and power plants. This indicator accounts for the primary energy from fossil, nuclear and primary forest resources (i.e. original forests that are destroyed and replaced by farmland) defined in terms of primary energy to final energy - kWh_{PE}/kWh_{FE}.

$$PE = FE * \mathrm{PEF}$$

Since the provenance of electrical energy at the plug varies widely from country to country due to their power generation and import mixes, the adopted values are reported in Table 6 and refer to the “Primary Energy Factors and Members States Energy Regulations” document [6] .

Table 6 – Values of PEF

	PEF
	[kWh_{PE}/kWh_{FE}]
Electricity	2.3
Main gas	1.1

- CO2 emissions

The emission of CO_2 is another indicator that gives an estimation of the impact that the proposed solutions have on the environment. For calculating this value, it is needed to calculate the emission factor for electricity or gas production. Following the indication of the “Covenant of Mayors – Technical annex to the SEAP template instruction document: The emission factors” [7], the following European average values are used:

Table 7 – Values of CO2 emissions factor

	Standard emission factor
	[t CO_2/MWh_e]
Electricity	0.46
Main gas	0.202

2.3.3 Comfort performance indicators

The EN 15251 introduces a method to evaluate the comfort conditions over time. The resulting KPI is "the time during which the actual operative temperature exceeds the specified range during the occupied hours", "weighted by a factor which is a function depending on by how many degrees, the range has been exceeded". In other words, it is an indicator of how much and how long the operating temperature is outside the comfort band during the occupation period.

Here, this KPI is called weighted discomfort time (WDT). The indicator is simplified with respect to the one defined in the standard: adaptive comfort is not considered; therefore the comfort range is constant. The lower limit of the range is the winter set point minus the lower hysteresis band (e.g. 20-0.5=19.5°C) and the upper limit of the range is referred to the summer set point (e.g. 25+0.5=25.5°C). WDT is computed as a time integral of the difference between the ambient temperature and the closer range limit, when the ambient temperature is outside the range, otherwise it is zero.

$$WDT_{winter} = \int_{time} (19.5 - T)\, LT(T, 19.5)\, dt \qquad WDT_{summer} = \int_{time} (T - 20.5)\, GT(T, 20.5)\, dt$$

Where GT and LT are Boolean operators and means, respectively, "greater than" and "lower than". In some cases, it is more interesting to evaluate the maximum value of WDT (MAX WDT) for each discomfort occurrence, rather than its value at the end of the year/season. In that cases, the WDT is reset to zero whenever the ambient temperature returns within the range.

In the following analysed cases, the maximum *WDT* has been maintained below 1 h·°C as considered an acceptable discomfort rate. For this reason, it is not reported in the results but taken into consideration during the study.

2.3.4 Economic indicator

- For the economic indicator, the cost of energy for the consumed final energy is taken into account. Depending on the analysed location, a specific cost of electricity or gas has been assumed, based on the indications of [8] and [9]. Table 8 summarizes the adopted values.

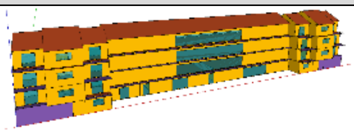
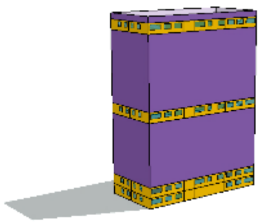
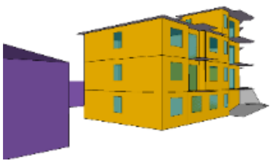
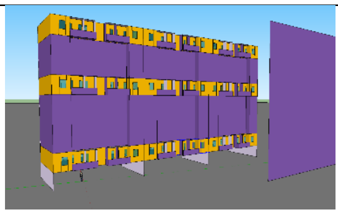
Table 8 – Cost of energy for each analysed climate

Climate zone	**Cost of energy - ELECTRICITY**	**Cost of energy - GAS**
	€/kWh	€/kWh
Continental	0.3088	0.0632
Oceanic	0.2122	0.0493
Mediterranean	0.2301	0.0769
Southern Dry	0.2403	0.0736
Europe	0.2159	0.0632

3 Description of the buildings and retrofit solutions (RS) variants

The reference buildings have been defined on the basis of geometric characteristics aiming at covering the most common typologies and, at the same time, having a variety of analysed cases. Table 9 summarizes the main reference buildings geometric characteristics. The four typologies differ for the number of floors, the horizontal development and the total heated area. Looking at the shape factor, the S/V ratio, the chosen building typologies range from 0.15 for a very compact building to 0.45 for a smaller building.

Table 9 – Reference buildings characteristics

Building typology		Number of floors	Number of dwellings per floor	Area tot	S/V
		[-]	[-]	[m²]	[-]
Low rise (LRMF)		4	15	4055	0.34
High rise (HRMF)		17	6	7140	0.15
Small MFH (SMFH)		4	2	712	0.45
Large MFH (LMFH)		8	2	7120	0.27

As mentioned in section 2, thermal characteristics depend on the specific climate. For the existing case pre-retrofit, average walls, roof, ground and windows transmittance for a building built between 1980 and 1990 are adopted. Walls construction changes depending on the building typology, but the total transmittance is the same for each climate. These values refer to the study conducted during the FP7 project iNSPiRe [10] and are reported in Table 10.

Table 10 – Transmittance values for reference buildings built between 1980-1990

	U_{walls}	U_{roof}	U_{ground}	U_{window}
	[W/m²·K]	*[W/m²·K]*	*[W/m²·K]*	*[W/m²·K]*
Continental	0.65	0.42	0.69	2.92
Oceanic	0.76	0.59	1.07	4.36
Mediterranean	1.00	1.24	1.51	4.03
Southern Dry	1.56	1.33	1.07	3.49

Thermal transmittances for the renovated cases aim at achieving the minimum requirements defined in each reference country when renovating. These are reported in Table 11 and implemented when retrofit packages are applied to the reference building.

Table 11 – Transmittance values defined by current regulations for buildings retrofit

	U_{walls}	U_{roof}	U_{ground}	U_{window}
	[W/m²·K]	*[W/m²·K]*	*[W/m²·K]*	*[W/m²·K]*
Continental	0.25	0.19	0.23	1.10
Oceanic	0.18	0.13	0.13	1.40
Mediterranean	0.29	0.26	0.34	2.00
Southern Dry	0.41	0.35	0.65	1.80

3.1 Building 1 – Low rise building - LRMF

3.1.1 Building typology

A low-rise building is characterized by a total number of floors less than 4 and it extends horizontally. The reference building for this typology develops through a ground floor plus three floors; it is north-south exposed. The building is composed by five blocks with three dwellings each: two 85 m² dwellings facing north and south and one 50m² dwelling facing south. In total, the building has 53 dwellings, 8 in the ground floor and 15 in the other floors.

Due to its shape, the building has a S/V ratio of 0.34 meaning that is quite compact (lower S/V ratio lower thermal losses).

The adopted modelling approach and more details on the building are presented in the following paragraph.

3.1.2 Building modelling approach

The reference low rise building is composed by five blocks all identical with exception of the ground floor. For the sake of computational effort, two representative blocks have been modelled with one thermal zone for the smaller dwelling and with two thermal zones, north side and south side, for the larger dwellings. The intermediate blocks are modelled as a unique zone. Figure 6 and Figure 7 show the 3D model of the south and north facades of the whole building.

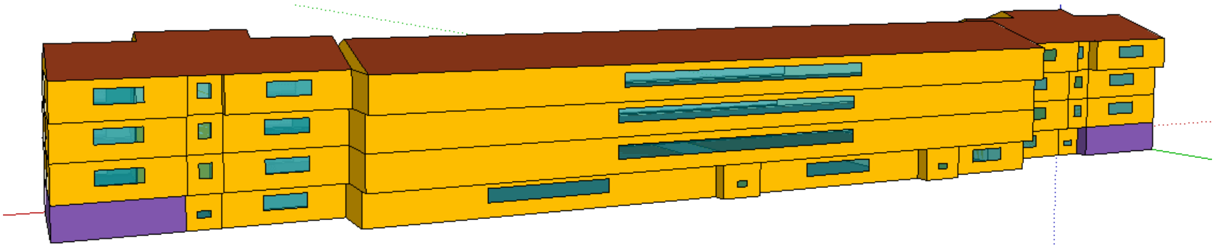


Figure 6 – 3D model - view of the North façade

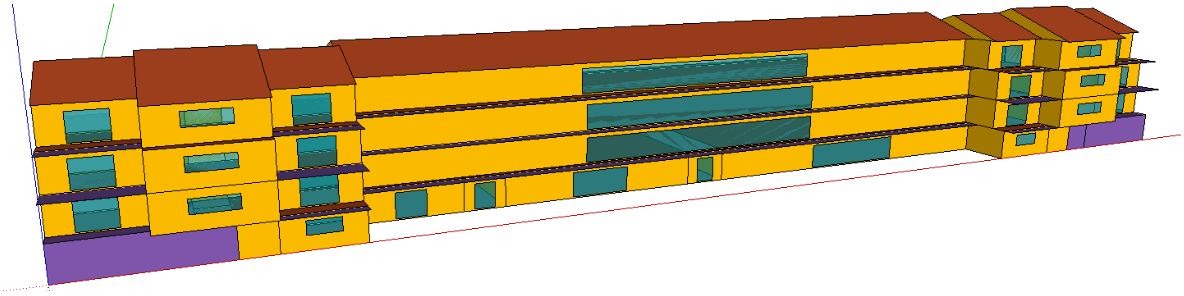


Figure 7 – 3D model - view of the South façade

Internal gains are accounted as contribution due to people occupancy, lighting and appliances use. In a multi-family house, due to the non-simultaneous behaviour of tenants, the profiles of occupancy, appliances and lighting are defined with stochastic trends [11]. For the appliances, current yearly overall consumption has been calculated on the basis of electric bills of the demo case. Peak values for internal gains, set-point temperatures in winter and summer, infiltration and ventilation rates assumed for the simulations are summarized in Table 12.

Table 12 – Boundary conditions for the building model

Occupancy	Value
Number of people per apartment	2-4
Sensible Heat	65 W
Latent Heat	55 W
Lighting	
Peak sensible heat	11 W/m²
Infiltration and ventilation	
Infiltration flow rate	0.10 vol/h
Natural Ventilation flow rate (pre-retrofit)	0.3 vo/h
Mechanical ventilation flow rate (post retrofit)	100 – 400 m³/hr
Set temperatures	
Schedule space heating	0-24 h
Heating set temperature	20°C
Cooling set temperature	25°C

3.1.3 Intervention on the envelope

Retrofit solutions for the envelope depends on the building typology and climate conditions.

The building typology characterizes external surfaces composition depending on the number of floors, building geometry and construction year. As a consequence, each building typology will have a specific wall construction. The reference thermal transmittance for each country for buildings built between 1980-1990 is reported in Table 10.

Solutions for reducing heating and cooling demands consist mainly on walls insulation and windows replacement. The target U value to be achieved through the renovation works is that defined in each country and reported in Table 11.

The following Table 13 summarizes the building walls construction specific of a low-rise building and the reference U-values referred to a building built between 1980-1990. Table 14 adds to the existing walls construction, additional insulation layer for achieving the target U_{values} for a renovated building and replaces the actual windows with more performant ones.

The considered insulation material is a mineral wool with thermal conductivity of 0.036 W/m·K.

Table 13 – Walls construction and U_{values} for the reference low-rise building in the four climates

LOW RISE Building - 1980-1990

CONTINENTAL

	Material	λ	l	U value
		W/m·K	m	W/K·m²
EXTERNAL WALL	Resistance int surface	0.13		
	Lime mortar	0.87	0.13	
	Mineral wool 035	0.04	0.04	
	Clinker hollow 2	0.58	0.04	0.65
	Gypsum plaster	0.35	0.02	
	Mineral wool 035	0.04		
	Resistance ext surface	0.04		
FLOORS	Resistance int surface	0.17		
	Mineral wool 035	0.04	0.00	
	Tile	1.00	0.01	
	Lime mortar	0.87	0.05	0.68
	Mineral wool 035	0.04	0.02	
	Lw concrete 1	0.39	0.30	
	Resistance ext surface	0.04		
ROOFS	Resistance int surface	0.10		
	Gypsum plaster	0.35	0.03	
	Perpendicular Air layer 10	1.00		
	Lw concrete 9	1.00	0.30	0.43
	Mineral wool 035	0.04	0.06	
	-			
	Resistance ext surface	0.04		
WINDOW	Fictive window		g value	2.83

OCEANIC

	Material	λ	l	U value
		W/m·K	m	W/K·m²
EXTERNAL WALL	Resistance int surface	0.13		
	Lime mortar	0.87	0.13	
	Mineral wool 035	0.04	0.04	
	Clinker hollow 2	0.58	0.04	0.71
	Gypsum plaster	0.35	0.02	
	Mineral wool 035	0.04		
	Resistance ext surface	0.04		
FLOORS	Resistance int surface	0.17		
	Mineral wool 035	0.04	0.00	
	Tile	1.00	0.01	
	Lime mortar	0.87	0.05	1.04
	Mineral wool 035	0.04	0.00	
	Lw concrete 2	0.44	0.30	
	Resistance ext surface	0.04		
ROOFS	Resistance int surface			
	Gypsum plaster	0.35	0.03	
	Perpendicular Air layer 10	1.00		
	Lw concrete 9	1.00	0.30	0.57
	Mineral wool 035	0.04	0.04	
	-			
	Resistance ext surface	0.04		
WINDOW	Fictive window		g value	4.14

MEDITERRANEAN

	Material	λ	l	U value
		W/m·K	m	W/K·m²
EXTERNAL WALL	Resistance int surface	0.13		
	Lime mortar	0.87	0.13	
	Mineral wool 035	0.04	0.02	
	Clinker hollow 2	0.58	0.04	0.99
	Gypsum plaster	0.35	0.02	
	Mineral wool 035	0.04		
	Resistance ext surface	0.04		
FLOORS	Resistance int surface	0.17		
	Mineral wool 035	0.04	0.00	
	Tile	1.00	0.01	
	Lime mortar	0.87	0.05	1.52
	Mineral wool 035	0.04	0.00	
	Lw concrete 7	0.79	0.30	
	Resistance ext surface	0.04		
ROOFS	Resistance int surface	0.10		
	Gypsum plaster	0.35	0.03	
	Perpendicular Air layer 10			
	Lw concrete 9	1.00	0.31	1.24
	Mineral wool 035	0.04	0.01	
	-	1.00		
	Resistance ext surface	0.04		
WINDOW	Fictive window		g value	4.14

SOUTHERN DRY

	Material	λ	l	U value
		W/m·K	m	W/K·m
EXTERNAL WALL	Resistance int surface	0.13		
	Lime mortar	0.87	0.13	
	Mineral wool 035	0.04	0.01	
	Clinker hollow 2	0.58	0.04	1.53
	Gypsum plaster	0.35	0.02	
	Mineral wool 035	0.04		
	Resistance ext surface	0.04		
FLOORS	Resistance int surface	0.17		
	Mineral wool 035	0.04	0.00	
	Tile	1.00	0.01	
	Lime mortar	0.87	0.05	1.04
	Mineral wool 035	0.04	0.00	
	Lw concrete 2	0.44	0.30	
	Resistance ext surface	0.04		
ROOFS	Resistance int surface	0.10		
	Gypsum plaster	0.35	0.03	
	Perpendicular Air layer 10			
	Lw concrete 9	1.00	0.30	1.32
	Mineral wool 050	0.05	0.01	
	-	1.00		
	Resistance ext surface	0.04		
WINDOW	Fictive window		g value	3.65

Table 14 – Walls construction and U_{values} for the low-rise building post-retrofit in the four reference climates

LOW RISE Building - POST RETROFIT

CONTINENTAL

	Material	λ	l	U value
		W/m·K	m	W/K·m²
EXTERNAL WALL	Resistance int surface			
	Lime mortar	0.87	0.13	
	Mineral wool 035	0.036	0.05	
	Clinker hollow 2	0.58	0.04	0.24
	Gypsum plaster	0.35	0.02	
	Mineral wool 035	0.036	0.09	
	Resistance ext surface			
FLOORS	Resistance int surface			
	Mineral wool 035	0.04	0.06	
	Tile	1.00	0.01	
	Lime mortar	0.87	0.05	0.23
	Mineral wool 035	0.04	0.06	
	Lw concrete 1	0.39	0.30	
	Resistance ext surface			
ROOFS	Resistance int surface			
	Gypsum plaster	0.35	0.03	
	Perpendicular Air layer 10	1.00		
	Lw concrete 9	1.00	0.30	0.19
	Mineral wool 035	0.04	0.17	
	-	1.00		
	Resistance ext surface			
WINDOW			g value	1.06

OCEANIC

	Material	λ	l	U value
		W/m·K	m	W/K·m²
EXTERNAL WALL	Resistance int surface			
	Lime mortar	0.87	0.13	
	Mineral wool 035	0.04	0.05	
	Clinker hollow 2	0.58	0.04	0.18
	Gypsum plaster	0.35	0.02	
	Mineral wool 035	0.04	0.14	
	Resistance ext surface			
FLOORS	Resistance int surface			
	Mineral wool 035	0.04	0.06	
	Tile	1.00	0.01	
	Lime mortar	0.87	0.05	0.13
	Mineral wool 035	0.04	0.17	
	Lw concrete 1	0.39	0.30	
	Resistance ext surface			
ROOFS	Resistance int surface			
	Gypsum plaster	0.35	0.03	
	Perpendicular Air layer 10	1.00		
	Lw concrete 9	1.00	0.30	0.13
	Mineral wool 035	0.04	0.25	
	-	1.00		
	Resistance ext surface			
WINDOW			g value	1.40

MEDITERRANEAN

	Material	λ	l	U value
		W/m·K	m	W/K·m²
EXTERNAL WALL	Resistance int surface			
	Lime mortar	0.87	0.13	
	Mineral wool 035	0.04	0.05	
	Clinker hollow 2	0.58	0.04	0.29
	Gypsum plaster	0.35	0.02	
	Mineral wool 035	0.04	0.07	
	Resistance ext surface			
FLOORS	Resistance int surface			
	Mineral wool 035	0.04	0.06	
	Tile	1.00	0.01	
	Lime mortar	0.87	0.05	0.35
	Mineral wool 035	0.04	0.01	
	Lw concrete 1	0.39	0.30	
	Resistance ext surface			
ROOFS	Resistance int surface			
	Gypsum plaster	0.35	0.03	
	Perpendicular Air layer 10	1.00		
	Lw concrete 9	1.00	0.30	0.25
	Mineral wool 035	0.04	0.12	
	-	1.00		
	Resistance ext surface			
WINDOW			g value	2.12

SOUTHERN DRY

	Material	λ	l	U value
		W/m·K	m	W/K·m
EXTERNAL WALL	Resistance int surface			
	Lime mortar	0.87	0.13	
	Mineral wool 035	0.04	0.05	
	Clinker hollow 2	0.58	0.04	0.40
	Gypsum plaster	0.35	0.02	
	Mineral wool 035	0.04	0.03	
	Resistance ext surface			
FLOORS	Resistance int surface			
	Mineral wool 035	0.04	0.02	
	Tile	1.00	0.01	
	Lime mortar	0.87	0.05	0.62
	Mineral wool 035	0.04	0.00	
	Lw concrete 1	0.39	0.30	
	Resistance ext surface			
ROOFS	Resistance int surface			
	Gypsum plaster	0.35	0.03	
	Perpendicular Air layer 10	1.00		
	Lw concrete 9	1.00	0.30	0.35
	Mineral wool 035	0.04	0.08	
	-	1.00		
	Resistance ext surface			
WINDOW			g value	1.73

For the sake of model simplicity, envelope insulation is meant as a traditional insulation to be applied on the external side of the façade. However, the multifunctional façade studied within the BuildHeat project [12] covers perfectly same functions with the additional advantages of:

- Containing the structure for placing new pipes;
- Being modular and therefore flexible for different applications;
- Reducing the installation works as it is pre-fabricated;
- Having a changeable finishing layer for being more adaptable to the different contexts.

3.2 Building 2 – High rise building - HRMF

3.2.1 Building typology

A high-rise building is characterized by a vertical dimension that is predominant with respect to the horizontal one, therefore it has a large number of floors.

The reference building for this typology has 17 floors with 6 apartments each. The total number of apartments is 102. The facades of the building are oriented at 45° with respect to the cardinal directions. Figure 8 shows the exposure of the single apartments in a typical floor. Apartment 2 is mainly exposed towards North whereas apartment 5 is mainly exposed toward South. Apartments 3 and 4 have only one side exposed externally, and respectively towards South-East and North-West. All the apartments have a regular shape and no balconies are present. The building has a quite compact shape, and, consequently, a low S/V ratio (0.15). The floor area of apartments 1, 2, 5 and 6 is 80 m^2, and the floor area of apartments 3 and 4 is 56 m^2.

Figure 8 – High-rise building – orientation and geometry of apartments in a typical floor

3.2.2 Building modelling approach

The assumption for the present analysis is that the mid-floor is the more representative floor of the building, as there are 15 mid-floors with same boundary conditions over the total 17 floors. Therefore, the KPIs expressed in terms of annual energy (thermal or electric) are calculated for the typical mid floor and multiplied by 17. However, in order to detect possible large differences in the heating or cooling demand between the apartments of the building, also the top and the ground floors are modelled, as shown in the 3D model of the building in Figure 9.

Internal gains are accounted as contribution due to people occupancy, lighting and appliances use. Different profiles of people activity are used, to account for the non-simultaneous behaviour of the tenants. The profiles of occupancy are stochastic [10] and consist of time series of values denoting whether people are active, sleeping, or away. Appliances and lighting are defined according to the people presence. A continuous constant gain is due to appliances (for example stand-by or fridge) and others, including lighting, is related to occupants' activity, which is zero when people are away or sleeping. Peak values for internal gains, set-point temperatures in winter and summer, infiltration and ventilation rates assumed for the simulations are summarized in Table 15.

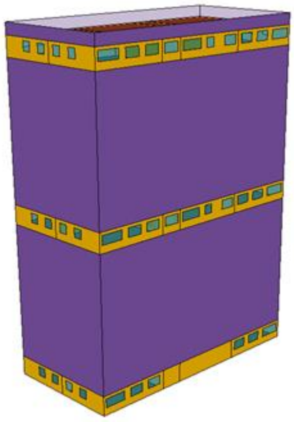


Figure 9 – High-rise building - 3D model view

Table 15 – Boundary conditions for the building model

Occupancy	Value
Number of people (80 m^2 apartments)	3
Number of people (56 m^2 apartments)	2
Power (standing, relaxed)	126 W/person
Power (sleeping)	76 W/person
Appliances and lighting	
Appliances continuous	105 W
Appliances and lighting (when people active)	508 W
Infiltration and ventilation	
Infiltration flow rate	0.1 vol/h
Natural Ventilation flow rate	0.3 vol/h
Set temperatures	
Schedule space heating	0-24 h
Heating set temperature	20°C
Cooling set temperature	25°C

3.2.3 Intervention on the envelope

Table 16 summarizes the building walls construction specific of a high-rise building and the reference U-values are referred to a building built between 1980-1990. In Table 17 additional insulation layers are added to the existing wall constructions, in order to achieve the target U_{values} for a renovated building. The table shows a double air layer for the external wall since the material in between was removed in order to simplify the stratigraphy. This simplification is acceptable since that layer has a negligible impact on the U value of the wall. The actual windows are replaced with more performant ones. The considered insulation material is a mineral wool with thermal conductivity of 0.036 W/m·K.

Table 16 – Walls construction and U_{values} for the reference high-rise building in the four climates

	HIGH RISE Building - 1980-1990															
	CONTINENTAL				OCEANIC				MEDITERRANEAN				SOUTHERN DRY			
	Material	**λ**	**l**	U value	**Material**	**λ**	**l**	U value	**Material**	**λ**	**l**	U value	**Material**	**λ**	**l**	U value
		W/m·K	m	W/K·m²		W/m·K	m	W/K·m²		W/m·K	m	W/K·m²		W/m·K	m	W/K·m²
EXTERNAL WALL	Resistance int surface	0.13			Resistance int surface	0.13			Resistance int surface	0.13			Resistance int surface	0.13		
	Plasterboard	0.16	0.014		Plasterboard	0.16	0.014		Plasterboard	0.16	0.014		Plasterboard	0.16	0.014	
	Perpendicular Air layer 10	1.00		0.65	Perpendicular Air layer 10	1.00		0.71	Perpendicular Air layer 10	1.00		0.79	Perpendicular Air layer 10	1.00		1.54
	Perpendicular Air layer 10	1.00			Perpendicular Air layer 10	1.00			Perpendicular Air layer 10	1.00			Perpendicular Air layer 10	1.00		
	Concrete slab	1.13	0.225		Concrete slab	1.13	0.225		Concrete slab	1.13	0.225		Concrete slab	1.13	0.150	
	Mineral wool 035	0.04	0.030		Mineral wool 035	0.04	0.025		Mineral wool 035	0.04	0.020		Mineral wool 035	0.04	0.000	
	Resistance ext surface	0.04			Resistance ext surface	0.04			Resistance ext surface	0.04			Resistance ext surface	0.04		
FLOORS	Resistance int surface	0.17			Resistance int surface	0.17			Resistance int surface	0.17			Resistance int surface	0.17		
	Timberfloor	0.14	0.030		Timberfloor	0.14	0.030		Timberfloor	0.14	0.030		Timberfloor	0.14	0.030	
	-	1.00			-	1.00			-	1.00			-	1.00		
	Mineral wool 035	0.04	0.040	0.65	Mineral wool 035	0.04	0.020	1.02	Mineral wool 035	0.04	0.008	1.55	Mineral wool 035	0.04	0.020	1.02
	-	1.00			-	1.00			-	1.00			-	1.00		
	-	1.00			-	1.00			-	1.00			-	1.00		
	Resistance ext surface	0.04			Resistance ext surface	0.04			Resistance ext surface	0.04			Resistance ext surface	0.04		
ROOFS	Resistance int surface	0.10			Resistance int surface	0.10			Resistance int surface	0.10			Resistance int surface	0.10		
	Plasterboard	0.16	0.010		Plasterboard	0.16	0.010		Plasterboard	0.16	0.010		Plasterboard	0.16	0.010	
	Fibreglass	0.04	0.085		Fibreglass	0.04	0.055		Fibreglass	0.04	0.020		Fibreglass	0.04	0.020	
	Roofdeck	0.14	0.019	0.41	Roofdeck	0.14	0.019	0.58	Roofdeck	0.14	0.019	1.19	Roofdeck	0.14	0.019	1.19
	-	1.00			-	1.00			-	1.00			-	1.00		
	-	1.00			-	1.00			-	1.00			-	1.00		
	Resistance ext surface	0.04			Resistance ext surface	0.04			Resistance ext surface	0.04			Resistance ext surface	0.04		
WINDOW				2.83				4.14				4.14				3.65

Table 17– Walls construction and U_{values} for the low-high building post-retrofit in the four reference climates

	HIGH RISE Building - POST RETROFIT															
	CONTINENTAL				OCEANIC				MEDITERRANEAN				SOUTHERN DRY			
	Material	**λ**	**l**	U value	**Material**	**λ**	**l**	U value	**Material**	**λ**	**l**	U value	**Material**	**λ**	**l**	U value
		W/m·K	m	W/K·m²		W/m·K	m	W/K·m²		W/m·K	m	W/K·m²		W/m·K	m	W/K·m²
EXTERNAL WALL	Resistance int surface	0.13			Resistance int surface	0.13			Resistance int surface	0.13			Resistance int surface	0.13		
	Plasterboard	0.16	0.014		Plasterboard	0.16	0.014		Plasterboard	0.16	0.014		Plasterboard	0.16	0.014	
	Perpendicular Air layer	1.00		0.25	Perpendicular Air layer	1.00		0.18	Perpendicular Air layer	1.00		0.29	Perpendicular Air layer	1.00		0.40
	Perpendicular Air layer	1.00			Perpendicular Air layer	1.00			Perpendicular Air layer	1.00			Perpendicular Air layer	1.00		
	Concrete slab	1.13	0.225		Concrete slab	1.13	0.225		Concrete slab	1.13	0.225		Concrete slab	1.13	0.225	
	Mineral wool 035	0.04	0.120		Mineral wool 035	0.04	0.170		Mineral wool 035	0.04	0.100		Mineral wool 035	0.04	0.065	
	Resistance ext surface	0.04			Resistance ext surface	0.04			Resistance ext surface	0.04			Resistance ext surface	0.04		
FLOORS	Resistance int surface	0.17			Resistance int surface	0.17			Resistance int surface	0.17			Resistance int surface	0.17		
	Timberfloor	0.14	0.030		Timberfloor	0.14	0.030		Timberfloor	0.14	0.030		Timberfloor	0.14	0.030	
	-	1.00			-	1.00			-	1.00			-	1.00		
	Mineral wool 035	0.04	0.140	0.23	Mineral wool 035	0.04	0.260	0.13	Mineral wool 045	0.04	0.110	0.34	Mineral wool 035	0.04	0.040	0.65
	-	1.00			-	1.00			-	1.00			-	1.00		
	-	1.00			-	1.00			-	1.00			-	1.00		
	Resistance ext surface	0.04			Resistance ext surface	0.04			Resistance ext surface	0.04			Resistance ext surface	0.04		
ROOFS	Resistance int surface	0.10			Resistance int surface	0.10			Resistance int surface	0.10			Resistance int surface	0.10		
	Plasterboard	0.16	0.010		Plasterboard	0.16	0.010		Plasterboard	0.16	0.010		Plasterboard	0.16	0.010	
	Fibreglass	0.04	0.200		Fibreglass	0.04	0.300		Fibreglass	0.04	0.140		Fibreglass	0.04	0.100	
	Roofdeck	0.14	0.019	0.19	Roofdeck	0.14	0.019	0.13	Roofdeck	0.14	0.019	0.26	Roofdeck	0.14	0.019	0.35
	-	1.00			-	1.00			-	1.00			-	1.00		
	-	1.00			-	1.00			-	1.00			-	1.00		
	Resistance ext surface	0.04			Resistance ext surface	0.04			Resistance ext surface	0.04			Resistance ext surface	0.04		
WINDOW				1.06				1.40				2.12				1.73

3.3 Building 3 – Small Multi-Family House - SMFH

3.3.1 Building typology

A small multi-family house is composed by a small number of floors and about two dwellings per floor. The reference building for this typology has 4 floors and the 8 apartments have a floor area of 89 m² each. The apartments are East and West oriented. The South façade is supposed to be external while the Northern one bounds with another building. The building has a S/V ratio equal to 0.45 that indicates a non-compact multi family houses.

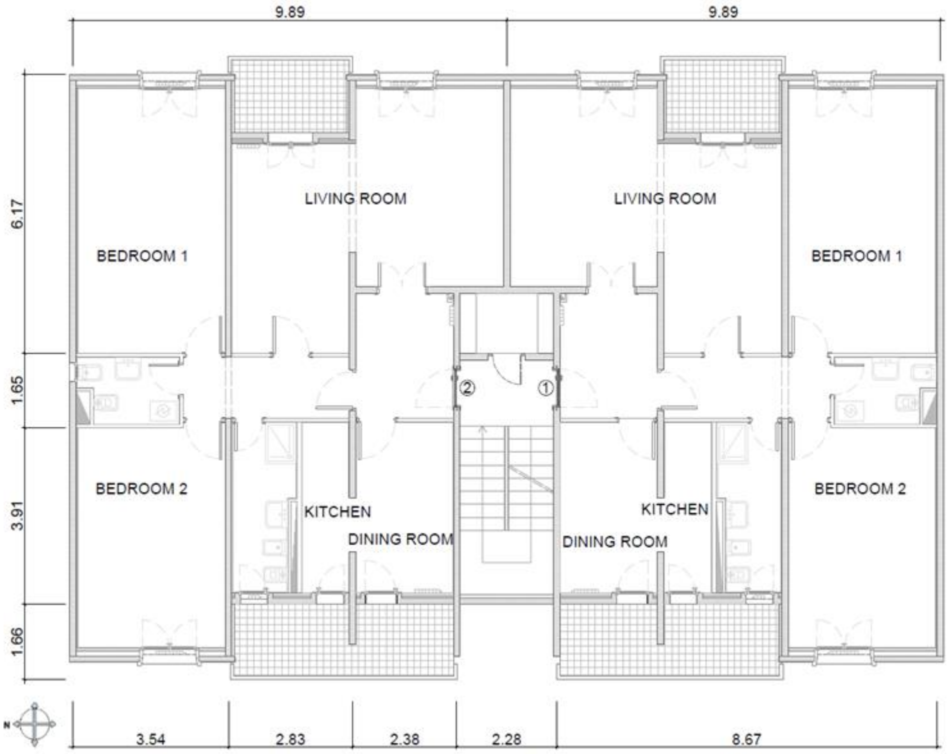


Figure 10 – Small multi-family house – orientation and geometry of a typical apartment

3.3.2 Building modelling approach

The building model has 3 floors instead of 4. Assuming that the behaviour of the two mid-floors is the same as they have the same boundary conditions, only the top floor, the first floor and one mid-floor are modelled, each with two apartments. The energy demand and consumption of the mid-floor is multiplied by 2 in order to reproduce the energy behaviour of the whole building. The geometric model is derived by the building used for the "large multi-family house" typology (see paragraph 3.4), by considering one over five staircases, the southern one.

3.3.3 Intervention on the envelope

The building walls construction of the small multi-family house in the pre and post-retrofit scenarios, are the same adopted in the large multi-family house. The reader can therefore refer to paragraph 3.4.3 for this information.

3.4 Building 4 - Large Multi-Family House - LMFH

3.4.1 Building typology

A large multi-family house is characterized by more than four floors and generally includes more than one staircase. The reference building for this typology has 5 staircases (see Figure 11), each serving 16 apartments on 8 floors. The total number of apartments is 80 with same geometry and a floor area of 89 m^2. The apartments exposure is mainly towards East and West. The apartments belonging to the North and South staircases have also facades exposed toward these directions, without windows. The first floor is not adjacent to the ground, it is raised (i.e. the floor slab is exposed to external air). The shape of the apartments is quite compact, apart for the recesses of the balconies, and the S/V ratio is 0.27.

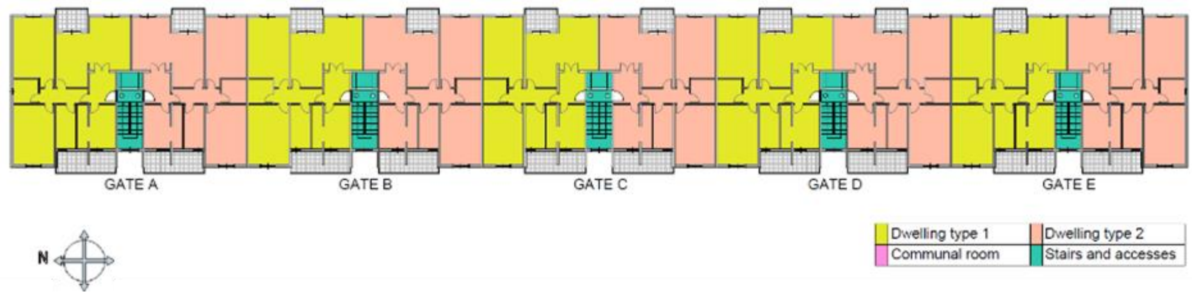


Figure 11 – Large multi-family house – orientation and geometry of the apartments and shape of the building plant.

3.4.2 Building modelling approach

The 5 blocks of apartments shown in Figure 11 differ from each other for the external boundary conditions. However, the 3 central blocks have the same exposure conditions and therefore their dynamic behaviour can be represented by simulating only one central block. The building model was simplified in order to achieve an affordable computational time and a reliable model. As shown in Figure 12, the model has 3 staircases, and 3 floors (the first floor, the top floor and one mid-floor) with a total number of 18 apartments. The apartments to be simulated have been selected in order to reproduce the energy behaviour of the whole building.

Figure 12 Large multi-family house – 3D model view

Occupancy	Value
Number of people per dwelling	3
Sensible heat	65 W/person
Latent heat	55 W/person
Appliances and lighting	
Peak sensible heat	10 W/m²
Stand-by sensible heat (min value)	2 W/m²
Infiltration and ventilation	
Infiltration flow rate	0.1 vol/h
Mechanical Ventilation flow rate	0.3 vol/h
Set temperatures	
Schedule space heating	0-24 h
Heating set temperature	20°C
Cooling set temperature	25°C

3.4.3 Intervention on the envelope

Table 18 and Table 19 summarize the building walls construction for a large multi-family house. U values reported in Table 18 refer to a building built between 1980-1990 while the ones in Table 19 includes additional insulation layers in order to achieve the target U values for a renovated building. The actual windows are replaced with more performant ones. The insulation material is a mineral wool with thermal conductivity of 0.036 W/m·K.

Table 18 – Walls construction and U values for the reference large multi-family house in the four climates in the pre-retrofit scenario

	MULTI FAMILY HOUSE - 1980-1990															
	CONTINENTAL				OCEANIC				MEDITERRANEAN				SOUTHERN DRY			
	Material	**λ**	**l**	U value	**Material**	**λ**	**l**	U value	**Material**	**λ**	**l**	U value	**Material**	**λ**	**l**	U value
		W/m·K	m	W/K·m²		W/m·K	m	W/K·m²		W/m·K	m	W/K·m²		W/m·K	m	W/K·m²
EXTERNAL WALL	Resistance int surface	0.13			Resistance int surface	0.13			Resistance int surface	0.13			Resistance int surface	0.13		
	Gypsym mortar	0.70	0.080		Gypsym mortar	0.70	0.080		Gypsym mortar	0.70	0.080		Gypsym mortar	0.70	0.080	
	Perpendicular Air layer 1	1.00			Perpendicular Air layer 1	1.00			Perpendicular Air layer 1	1.00			Perpendicular Air layer 1	1.00		
	Hollow block 2K 7	0.76	0.100	0.65	Hollow block 2K 7	0.76	0.100	0.76	Hollow block 2K 7	0.76	0.100	1.00	Hollow block 2K 7	0.76	0.150	1.56
	Mineral wool 035	0.04	0.036		Mineral wool 035	0.04	0.028		Mineral wool 045	0.04	0.020		Cement mortar	1.40	0.040	
	-	1.00			-	1.00			-	1.00			-	1.00		
	Resistance ext surface	0.04			Resistance ext surface	0.04			Resistance ext surface	0.04			Resistance ext surface	0.04		
FLOORS	Resistance int surface	0.17			Resistance int surface	0.17			Resistance int surface	0.17			Resistance int surface	0.17		
	Ceramics	1.20	0.030		Ceramics	1.20	0.030		Ceramics	1.20	0.030		Ceramics	1.20	0.030	
	Lw concrete 1	0.39	0.030		Lw concrete 1	0.39	0.030		Lw concrete 1	0.39	0.020		Lw concrete 1	0.39	0.030	
	Hollow block 2K 1	0.29	0.160	0.69	Hollow block 2K 1	0.29	0.160	1.07	Hollow block 2K 3	0.39	0.120	**1.50**	Hollow block 2K 1	0.29	0.160	1.07
	Mineral wool 035	0.04	0.021		Gypsum plaster	0.35	0.025		Gypsum plaster	0.35	0.025		Gypsum plaster	0.35	0.025	
	-	1.00			-	1.00			-	1.00			-	1.00		
	Resistance ext surface	0.04			Resistance ext surface	0.04			Resistance ext surface	0.04			Resistance ext surface	0.04		
ROOFS	Resistance int surface	0.10			Resistance int surface	0.10			Resistance int surface	0.10			Resistance int surface	0.10		
	Gypsum plaster	0.35	0.020		Gypsum plaster	0.35	0.020		Gypsum plaster	0.35	0.020		Gypsum plaster	0.35	0.020	
	Lw concrete 3	0.49	0.150		Lw concrete 3	0.49	0.150		Lw concrete 3	0.49	0.150		Lw concrete 3	0.49	0.150	
	Bitumen	0.17	0.005	0.42	Bitumen	0.17	0.005	0.59	Bitumen	0.17	0.005	**1.24**	Bitumen	0.17	0.005	1.33
	Mineral wool 035	0.04	0.067		Mineral wool 035	0.04	0.042		Mineral wool 045	0.04	0.012		Mineral wool 035	0.04	0.008	
	-	1.00			-	1.00			-	1.00			-	1.00		
	Resistance ext surface	0.04			Resistance ext surface	0.04			Resistance ext surface	0.04			Resistance ext surface	0.04		
WINDOW				2.83				4.14				4.14				3.65

Table 19 – Walls construction and U values for the reference large multi-family house in the four climates in the post-retrofit scenario

	MULTI FAMILY HOUSE - POST RETROFIT															
	CONTINENTAL				OCEANIC				MEDITERRANEAN				SOUTHERN DRY			
	Material	**λ**	**l**	U value	**Material**	**λ**	**l**	U value	**Material**	**λ**	**l**	U value	**Material**	**λ**	**l**	U value
		W/m·K	m	W/K·m²		W/m·K	m	W/K·m²		W/m·K	m	W/K·m²		W/m·K	m	W/K·m²
EXTERNAL WALL	Resistance int surface	0.13			Resistance int surface	0.13			Resistance int surface	0.13			Resistance int surface	0.13		
	Gypsym mortar	0.70	0.080		Gypsym mortar	0.70	0.080		Gypsym mortar	0.70	0.080		Gypsym mortar	0.70	0.080	
	Perpendicular Air layer 1	1.00			Perpendicular Air layer 1	1.00			Perpendicular Air layer 1	1.00			Perpendicular Air layer 1	1.00		
	Hollow block 2K 7	0.76	0.100	0.25	Hollow block 2K 7	0.76	0.100	0.18	Hollow block 2K 7	0.76	0.100	0.29	Hollow block 2K 7	0.76	0.100	0.41
	Mineral wool 035	0.04	0.125		Mineral wool 035	0.04	0.180		Mineral wool 035	0.04	0.105		Mineral wool 035	0.04	0.068	
	-	1.00			-	1.00			-	1.00			-	1.00		
	Resistance ext surface	0.04			Resistance ext surface	0.04			Resistance ext surface	0.04			Resistance ext surface	0.04		
FLOORS	Resistance int surface	0.17			Resistance int surface	0.17			Resistance int surface	0.17			Resistance int surface	0.17		
	Ceramics	1.20	0.030		Ceramics	1.20	0.030		Ceramics	1.20	0.030		Ceramics	1.20	0.030	
	Lw concrete 1	0.39	0.030		Lw concrete 1	0.39	0.030		Lw concrete 1	0.39	0.030		Lw concrete 1	0.39	0.030	
	Hollow block 2K 1	0.29	0.160	0.23	Hollow block 2K 1	0.29	0.160	0.13	Hollow block 2K 1	0.29	0.160	0.34	Hollow block 2K 1	0.29	0.160	0.65
	Mineral wool 035	0.04	0.125		Mineral wool 035	0.04	0.250		Mineral wool 035	0.04	0.074		Mineral wool 035	0.04	0.024	
	-	1.00			-	1.00			-	1.00			-	1.00		
	Resistance ext surface	0.04			Resistance ext surface	0.04			Resistance ext surface	0.04			Resistance ext surface	0.04		
ROOFS	Resistance int surface	0.10			Resistance int surface	0.10			Resistance int surface	0.10			Resistance int surface	0.10		
	Gypsum plaster	0.35	0.020		Gypsum plaster	0.35	0.020		Gypsum plaster	0.35	0.020		Gypsum plaster	0.35	0.020	
	Lw concrete 3	0.49	0.150		Lw concrete 3	0.49	0.150		Lw concrete 3	0.49	0.150		Lw concrete 3	0.49	0.150	
	Bitumen	0.17	0.005	0.19	Bitumen	0.17	0.005	0.13	Bitumen	0.17	0.005	0.26	Bitumen	0.17	0.005	0.35
	Mineral wool 035	0.04	0.170		Mineral wool 035	0.04	0.250		Mineral wool 035	0.04	0.120		Mineral wool 035	0.04	0.085	
	-	1.00			-	1.00			-	1.00			-	1.00		
	Resistance ext surface	0.04			Resistance ext surface	0.04			Resistance ext surface	0.04			Resistance ext surface	0.04		
WINDOW				1.06				1.40				2.12				1.73

3.5 Retrofit solution 1 – Decentralized HVAC system

3.5.1 HVAC system

The reference case for the Retrofit Solution 1 (RS1) is a decentralized system composed by a gas boiler per dwelling for covering space heating and DHW production. The assumed efficiency for this kind of system is 0.85. Space cooling is covered by a non-performant split unit system with efficiency 2.5. In the reference case, it is not present a mechanical ventilation system.

Figure 13 – Schematic of the RS1 HVAC system

The HVAC system proposed within the RS1 is a three-in-one heat pump able to cover space heating and cooling loads, DHW production and ventilation air change. The studied solution refers to the Elfopack produced by Clivet [13]. This machine is composed by a mechanical ventilation unit with heat recover which takes fresh air from outside and blows directly to the ambient if there is no need of air conditioning. When the ambient needs to be heated up or cooled down, fresh air is mixed with recirculation air and therefore is pre-treated. Heat exchanged through an air-to-water coil brings supply air to the optimal temperature for guaranteeing the comfort temperature in the ambient. The compressor modules depending on the required heat capacity. The source side of the heat pump is composed by an exhaust coil which throws out internal air. The Elfopack can work also in free-cooling mode when there are the optimal conditions between external and internal air (Figure 14).

Figure 14 – Working modes of the Elfopack in 1) heating, 2) cooling and 3) free cooling mode (http://www.clivetlive.com/en/web/guest/elfopack1)

The Elfopack contains two 90 litres tanks for DHW production. They work in series for reducing stratification and are heated by exchanging heat with the compressor. During summer, DHW is freely generated by waste heat of space cooling production. A 3D view of the Elfopack with a section of internal composition is reported in Figure 7.

Figure 15 – 3D view and section of the Elfopack (http://www.clivetlive.com/en/web/guest/elfopack1)

Technical data of the Elfopack is reported in Table 20. The machine has a heating capacity of around 3 kW and cooling capacity of 2 kW. COP is assessed to be 3.83 resulting on a power capacity less than 1 kW. Air flow rate during the three working modes, ventilation only, heating/cooling and free cooling, are presented in the following.

Table 20 – Technical data of the Elfopack

Technical data	Units	Value
Heating capacity	kW	3.18
Thermodynamic COP	-	3.83
Cooling capacity	kW	2.14
Thermodynamic EER	-	2.95
Safety electrical heater	kW	1.20

The behaviour of the Elfo Pack has been modelled in terms of energy fluxes for assessing the system consumption and performance, and for investigating the interaction of the Elfo Pack with PV production. Figure 16 shows a representation of the Elfopack numerical model. The orange/blue arrows indicate energy fluxes in terms of heat exchanged /absorbed. On the top left of the figure, the air circuit is represented with the contributions of fresh and recirculation air. On the right side, there is the heat exchanger for charging the stratified DHW tank.

More details on the modelling of the HVAC system for the RS1 can be found in [14] with reference to the heating and cooling system of the Zaragoza demo case.

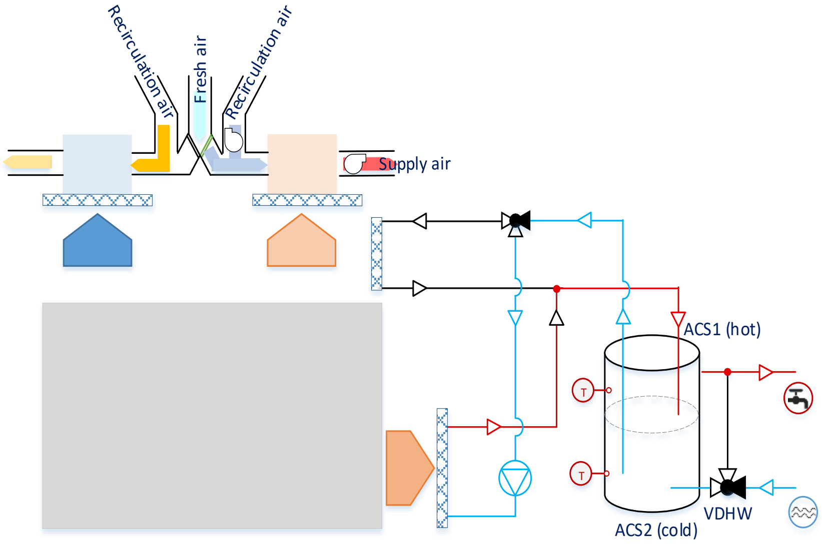


Figure 16 – Representation of the Elfopack numerical model

The Elfo Pack works as mechanical ventilation unit by blowing 100 m³/h of fresh air. When the internal zone needs to be heated up or cooled down, supply air is mixed with 300 m³/h of internal air and is treated in order to maintain the desired internal temperature. During summertime, heat recovery from space cooling is used for DHW uses.

In heating mode, the heat pump uses part of the produced thermal power for charging the DHW tanks through a heat exchanger. The two tanks are used in order to foster stratification. For the same reason, when there is a demand from the user, the tanks are not charged. The other part of thermal energy is used through the coil for warming up supply air. Air is pre-heated by mixing recirculation with fresh air. The source of the heat pump is another coil that exchanges with exhaust air (see Figure 17).

In case heating demand is high and requires the whole heat pump capacity, heating mode only is used and, in case of also DHW demand, an electric resistance is switched on (Figure 18 left). In all those situations where there is DHW demand only, the whole heat pump capacity is used through the heat exchanger (Figure 18 right).

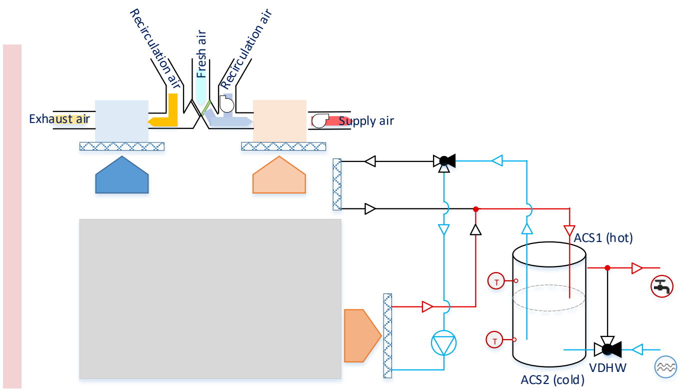


Figure 17 – Working scheme of the Elfo Pack for space heating + DHW production

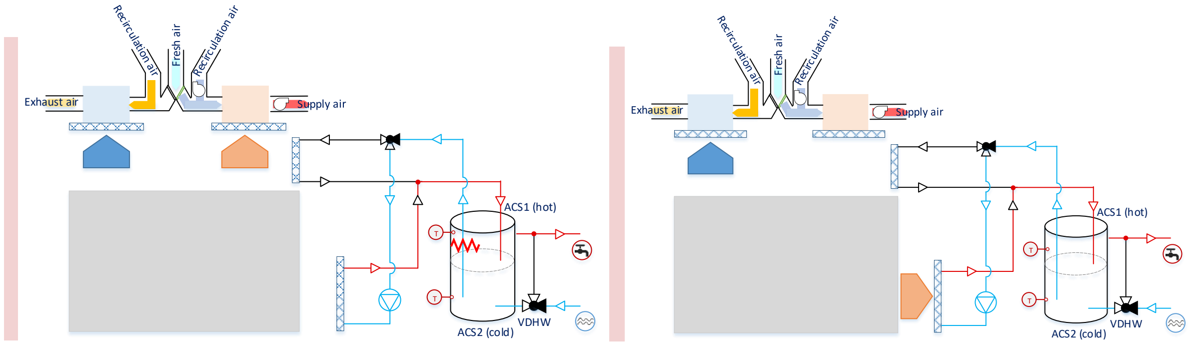


Figure 18 – Working scheme of the Elfo Pack for space heating only (left) and DHW production (right)

In cooling mode, heat pump cools down supply air that is the mix between fresh air and recirculation air while the exhaust coil is used as sink for the cooling production (Figure 19 left).

If during space cooling demand the sensor in the DHW tank reads a temperature lower than a setpoint, heat from the compressor is firstly recovered for heating up the DHW tanks and secondly removed through the exhaust coil (Figure 19 right).

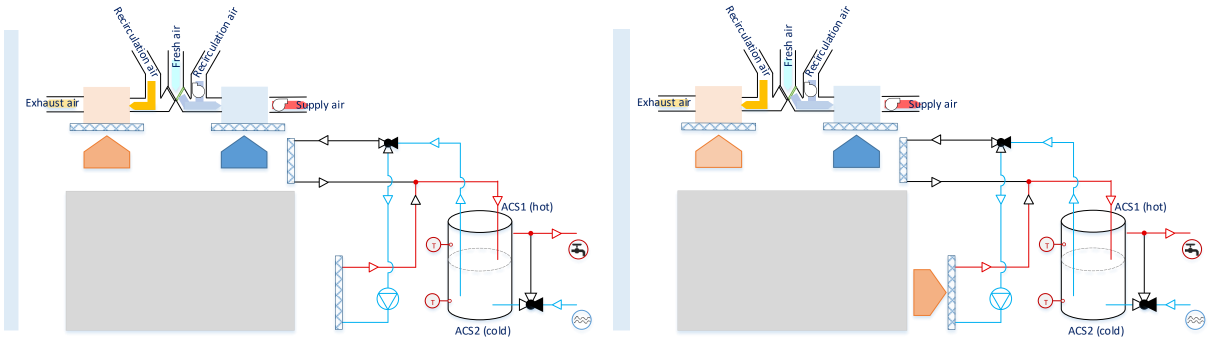


Figure 19 – Working scheme of the Elfo Pack for space cooling only (left) and space cooling + DHW production (right)

An additional working mode is represented by the possibility to cool down the zone with free cooling. In case the zone temperature is increasing and external air is lower than internal one, it is possible to supply a higher flux of fresh air (200 m³/h) avoiding to switch on the heat pump compressor (Figure 20).

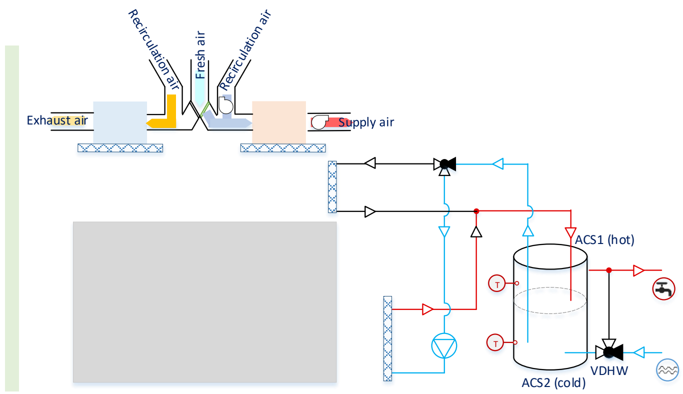


Figure 20 – Working scheme of the Elfo Pack for free cooling

3.5.2 Renewable energies

The Elfopack has an absorbed power at nominal conditions around 1 kW. For this reason, an equivalent PV field of peak power is considered for each dwelling. Depending on the available surface, panels are installed on the roof with an inclination of 30° or on the East and West façade with 90° slope. In this last case, 8 panels are installed instead of the 5 per dwelling on the roof (Table 21).

The RS1 includes an inverter able to directly exploit PV energy by the Elfopack when running.

In case of PV overproduction, an electric resistance is switched on in the DHW tanks for accumulating energy in the form of hot water.

Table 21 – Main characteristics of the single panel and of the whole PV field in the RS1

Type	Units	Value
Panel type		Monocrystalline silicon
Peak power	[W]	200
Dimensions (LxWxH)	[mm]	1580 x 808 x 35
Total panels on the roof	[-]	245
Slope on the roof	[°]	30
Total panels on the West and East facades	[-]	32
Slope on the façade	[°]	90

3.6 RS 2 – Decentralized generation and centralized water loop

3.6.1 HVAC system

In the reference pre-retrofit scenario for the Retrofit Solution 2 (RS2) the heating system for space conditioning and DHW production is composed by a centralized gas boiler. The assumed efficiency for this kind of system is 0.80. Energy distribution in the apartments is provided by radiators working at high temperature (around 70°C). Space cooling is covered with low performance split units with efficiency 2.5 and there is no mechanical ventilation.

The RS2 foresees the installation of a ground source heat pump (GSHP) of 6 kW for each dwelling for covering space heating, space cooling and DHW use. The GSHPs are connected to a brine loop as source side, composed by four risers with a circulation pump each, which, in turn, are connected to a bore field (see Figure 21 above).

Each apartment has 6 radiators of different sizes depending of the apartment floor area. However, only one radiator for apartment is modelled and the emission power is than multiplied by 6, as well as the inlet and outlet mass flow rate. Radiators have a maximum design supply temperature of 45°C (for outdoor temperature lower than -5°C), and it changes according to a climatic curve. The minimum supply temperature is 30°C, for outdoor temperatures greater than 15°C. This climatic control plus the inverter driven heat pump allows the system to adapt the emission powers to the climate and building load.

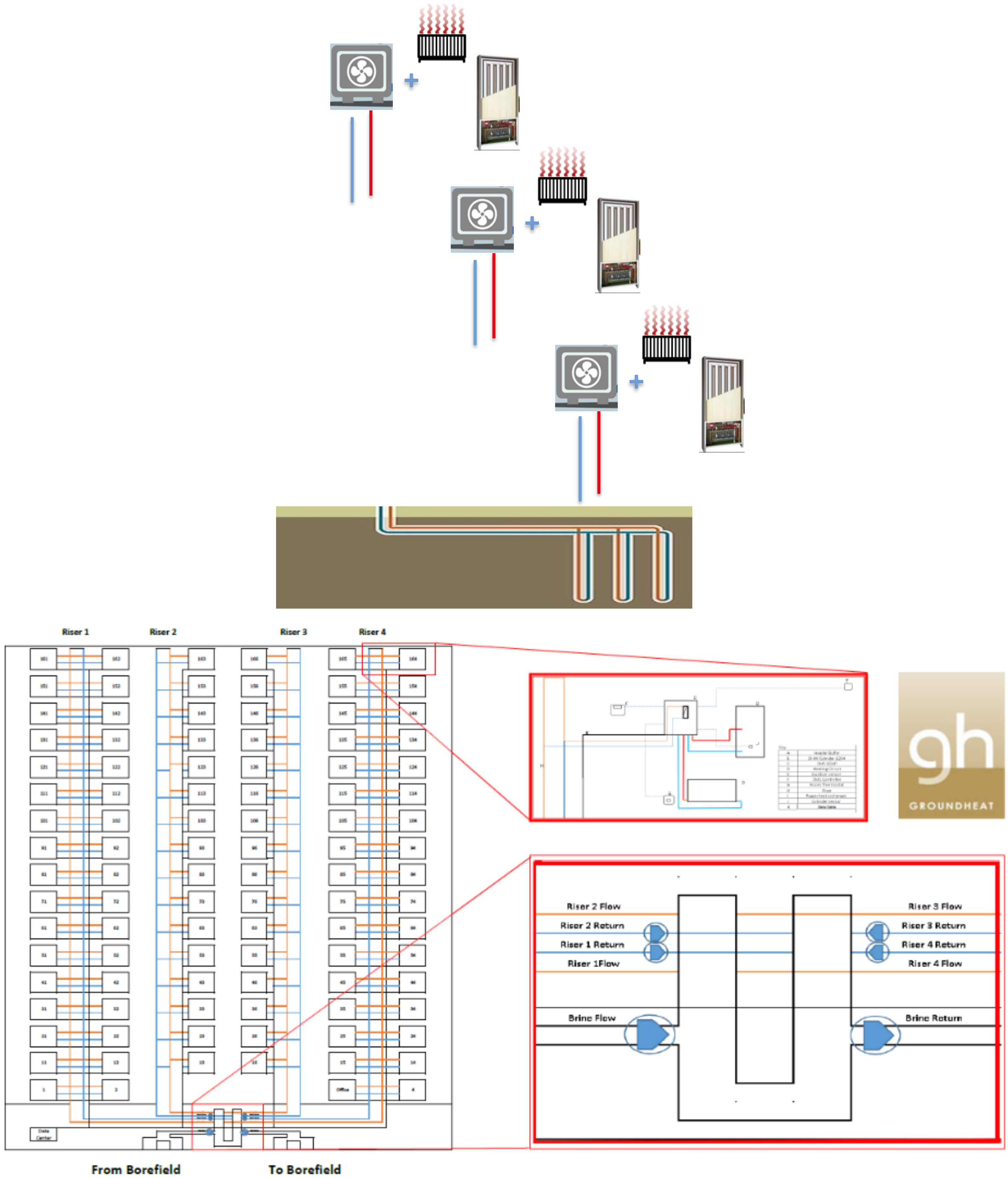


Figure 21 – Layout of the system at building level. Schematic of the decentralized heat pumps and bore field (above) and drawings of the risers through the building façade, generation system at dwelling level and detail of the bore field (below).

For the heating and DHW, a detailed model of the system components was developed, whereas space cooling was modelled in a simplified mode.

A scheme of the heating and the DHW system model at dwelling level is shown in Figure 22. The brine-to-water (B/W) heat pump supplies alternatively the radiators or the DHW storage, with priority for DHW 24/7. The heat pump performance for the heating operation is reported in Figure 23. Data is retrieved from a performance map of a commercial product. The 120 litres

DHW cylinder is modelled as a stratified tank with 5 temperature nodes and a temperature sensor located at 70% of the tank height.

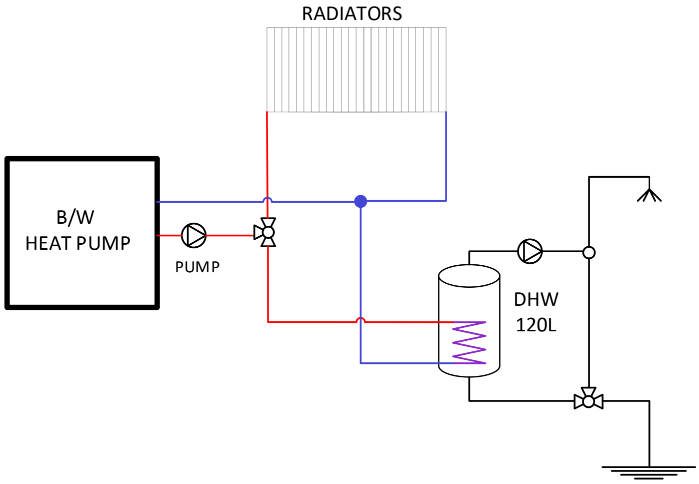


Figure 22 – Layout of the system at dwelling level

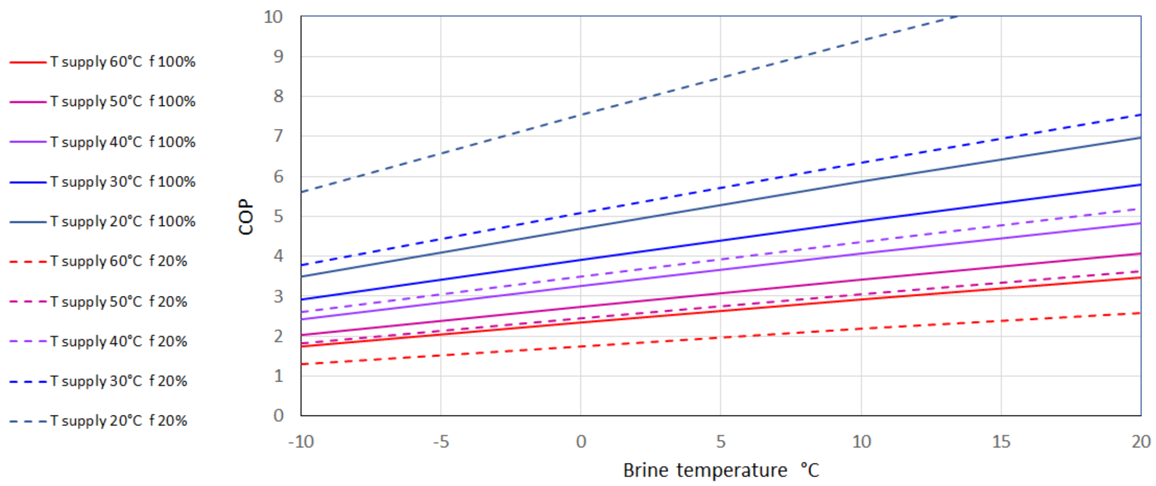


Figure 23 – Performance of the HP in heating mode

The heat pump is controlled at apartment level and is regulated by two operation schemes. The first, named SC_DHW, denotes the need for domestic hot water production and it indicates that the temperature inside the storage is below the set point (i.e., it needs to be charged). The second, named $SC\_HEATING$, is referred to the space heating of the apartment. As the priority is given to the DHW production, $SC\_HEATING$ is verified only if the DHW tank is charged and the apartment temperature is below the set point. The two working modes are regulated by the signals from the DHW tank sensor and the ambient thermostats. The setpoints and the relative hysteresis dead bands are reported in Table 22.

Table 22 – System control parameters

Sensor	Setpoint	Hysteresis dead band
DHW temperature (70% of the tank height)	45°C	0°C / +3°C
Ambient air temperature (winter)	20°C	±0.25°C

Regarding space cooling, a simplified modelling was adopted: ideal cooling demand is calculated by the building model, i.e. the ideal amount of thermal energy needed to maintain the indoor air temperature below 25°C. Cooling demand is assumed to be covered by means of the same heat pump which provides space heating and DHW. The electric energy consumption of the heat pumps is calculated assuming an EER as a linear function of the source temperature, with a fixed supply-return temperature of 7-12°C and a fixed compressor speed of 90 hz. The EER function is reported in Figure 24 and it is retrieved from a performance map of a commercial product.

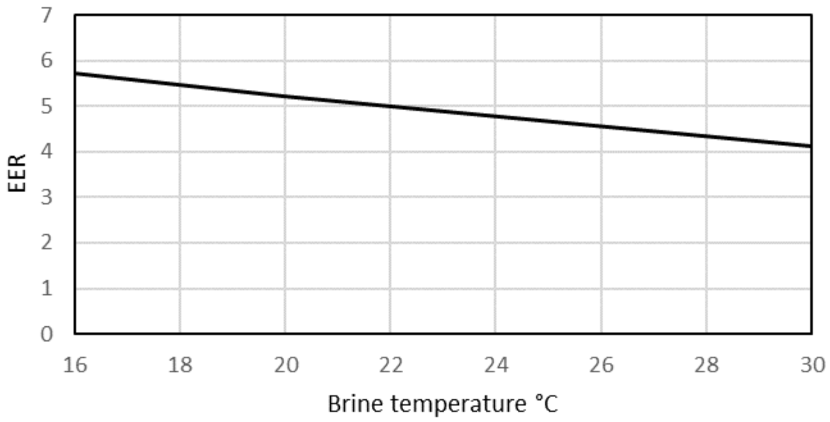


Figure 24 – Performance of the HP in cooling mode (load temperature equal to 7-12°C)

The brine loop risers pumps are assumed to operate according to the heat pump demand. When the heat pump is operating (in heating, cooling or DHW mode) the flow at source side is active, otherwise it is zero. The consumption of the risers pumps is calculated assuming an absorbed power proportional to the total mass flow of the building. For space heating and DHW production, pump consumption is included in the calculation of the simulation, while for space cooling, pump power consumption is hourly calculated and added to the heat pump consumption.

The temperature of the fluid rising from the ground is assumed to be slightly warmer (during winter) or colder (during summer) than the ground temperature. The ground temperature is calculated as a weighted average of the temperature of different layers of the ground down to 180 m deep (assumed length of the bore holes), and in particular:

- from the surface to 20 m deep (11%), a sinusoid annual profile according to the air temperature profile of the reference climate;
- from 20 m to 40 m (11%) a constant temperature equal to the annual average of the layer above;
- from 40 m to 180 m (78%) a temperature gradient of 3°C/100m.

3.6.2 Renewable energies

Two kinds of renewable energy sources are exploited with this retrofit solution: geothermal heat source and solar source by means of the photovoltaic modules.

The geothermal source is particularly interesting for the temperature that the ground can offer, which are more advantageous with respect to the external air, during both winter and summer. The ground temperature annual profile is less affected by the location than the air temperature profile.

Main characteristics of the PV panels are reported in Table 1Table 23. The PV field is composed of 210 panels installed on the roof with slope 30° and 120 installed on the south-west façade.

The two apartments on the south-west façade have 4 panels each for covering part of the electric load while the other dwellings plus the two on the ground floor can benefit of 3 panels each installed on the roof.

Table 23 – Characteristics of the single panel and of the whole installed PV field

Type	Units	Value
Panel type		Monocrystalline silicon
Peak power	[W]	200
Dimensions (LxWxH)	[mm]	1580 x 808 x 35
Total panels on the roof	[-]	210
Slope on the roof	[°]	30
Total panels on the South façade	[-]	120
Slope on the façade	[°]	90

3.7 RS 3 –Centralized HVAC system

3.7.1 HVAC system

The reference pre-retrofit scenario for the Retrofit Solution 3 (RS3) has a centralized system composed by a gas boiler that covers space heating. The assumed efficiency for this kind of system is 0.8. DHW production relies on individual electric boilers (one for each apartment). Space cooling is covered with low performance split units with efficiency 2.5 and there is no mechanical ventilation.

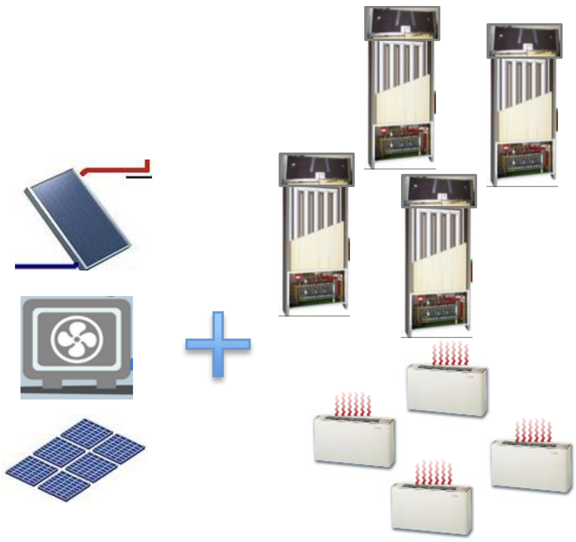


Figure 25 – Schematic of the HVAC system in RS3

The RS3 is applied to both large and small multi-family houses (LMFH and SMFH). When applied to the LMFH, each of the five staircases has an independent HVAC system based on a centralized air-to-water heat pump, located on the roof of the staircase block (Figure 25). Each heat pump can cover heating, cooling, and DHW demands for the apartments of the respective block. Performance map for COP and EER of the adopted heat pump are reported in Figure 26.

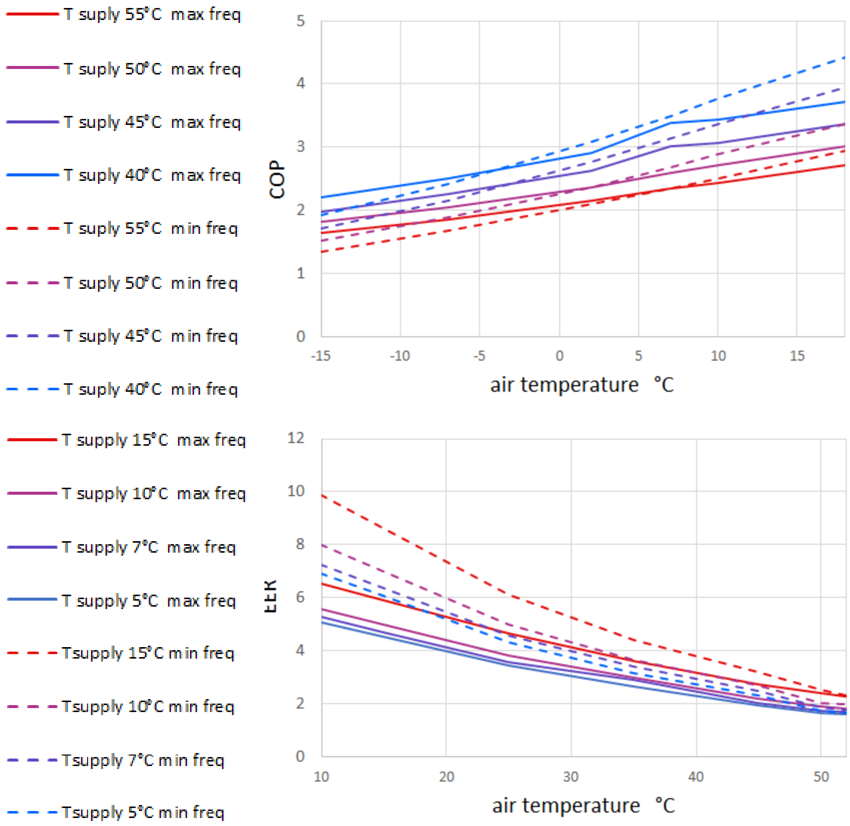


Figure 26 – Performance map of an air-to-water heat pump with variable compressor speed for different supply temperature. COP (above) and EER (below)

The South-facing block has solar thermal panels positioned vertically on the South façade, which can give a significant contribution to the DHW production. This contribution is accounted for the whole building.

When applied to the SMFH, the RS3 has the same configuration as for large MFH, but the generation system has to supply the demand of 8 apartments instead of 16 apartments. The solar thermal collector field supplies DHW for all the 8 apartments of the SMFH, therefore, in the SMFH a higher solar thermal share is expected.

The heat pump generation system on the roof includes a DHW storage tank of 1000 litres and a buffer tank of 500 litres for the heating and cooling distribution. All the dwellings have their own “Enerboxx”, a prototype of an innovative box that includes a 140 litres water storage tank for domestic hot water uses, a mechanical ventilation unit with heat recovery and a hydraulic module connected to the fan coils circuit for space heating and cooling.

The solar circuit connects the solar thermal collectors (STC) to the solar thermal energy storage (TES) and it is run by a fixed speed pump PM1 (see Figure 27), whose activation is based on three signals from different measured variables: radiation availability, temperature of the solar TES, and temperature difference between the STC exiting fluid and the solar TES.

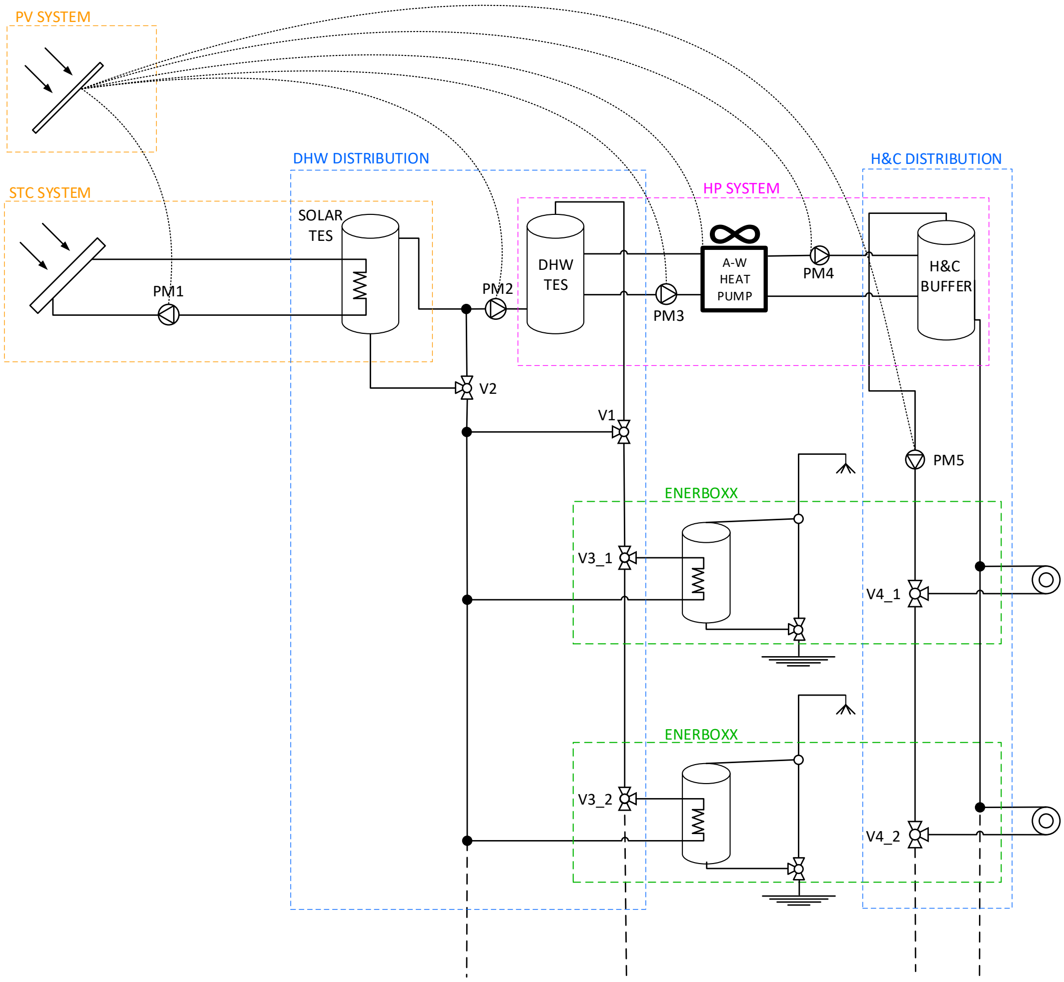
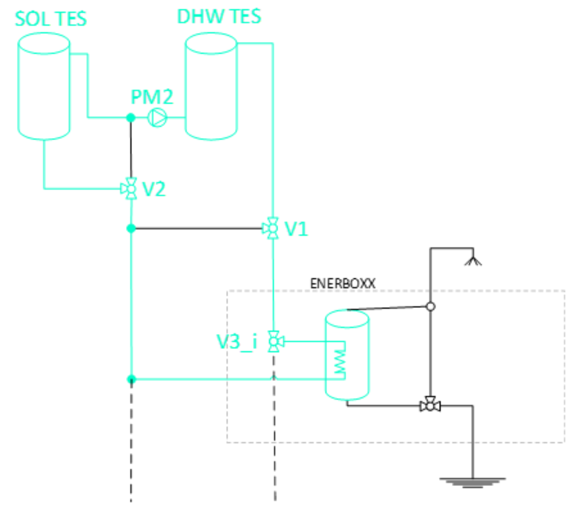


Figure 27 – Large and small multi-family house system layout

In case of excess of heat from the solar thermal field, the Enerboxx tanks can be overheated that is they can reach a temperature higher than their normal set point. The control of the DHW distribution is therefore based on two signals at staircase level (Solar and Overheating) plus one signal from the Enerboxx tank of each apartment (Enerboxx_i Charging). The signals can be explained as follows:

- Solar: the solar TES is warmer than DHW TES;
- Enerboxx Overheating: due to the contribution from solar collectors, the DHW tank has reached a temperature higher than its set-point; additional heat can be transferred to the tanks at dwelling level (Enerboxx) up to their second set point;
- Enerboxx_i Charging (one for each apartment): the tank in the Enerboxx has a temperature below the set-point, 45°C, and it needs to be heated. Therefore, the three-way valve belonging to this Enerboxx at dwelling level is open.

An additional condition (DHW_Distribution) is verified if the condition Enerboxx_i Charging is verified for at least one of the apartments. Depending on the conditions DHW_Distribution and Solar, one of the four cases in Figure 28 occurs.

<table>
<tr>
<td>
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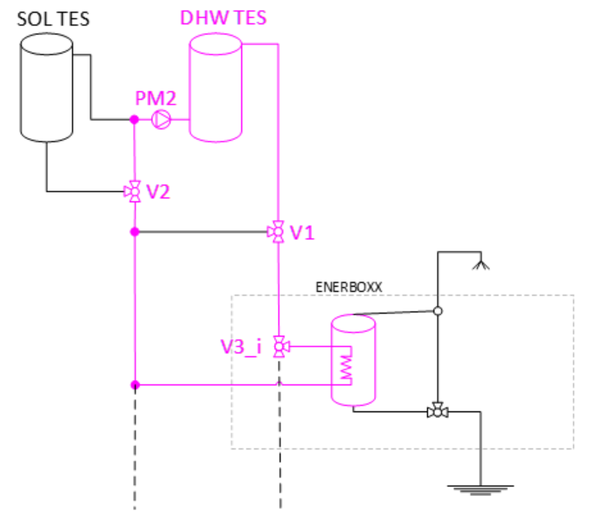
<td>
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</tr>
<tr>
<td>$\boldsymbol{Solar\ AND\ Distribution}$
The solar TES is warmer than the DHW TES, and at least in one apartment the ENERBOXX valve is open</td>
<td>$NOT(\boldsymbol{Solar})\ AND\ \boldsymbol{Distribution}$
The solar TES is not warmer than the DHW TES, and at least in one apartment the ENERBOXX valve is open</td>
</tr>
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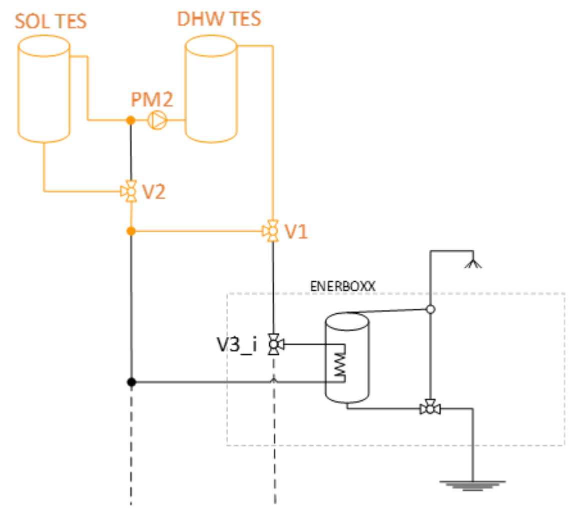
<td>
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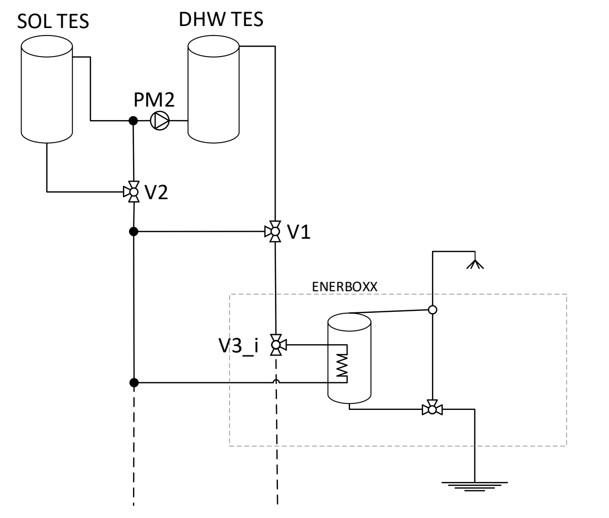
<td>
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</tr>
<tr>
<td>$\boldsymbol{Solar}\ AND\ NOT(\boldsymbol{Distribution})$
The solar TES is warmer than the DHW TES, and the ENERBOXX valves are closed in all the apartments</td>
<td>$NOT(\boldsymbol{Solar})\ AND\ NOT(\boldsymbol{Distribution})$
The solar TES is not warmer than the DHW TES and the ENERBOXX valves are closed in all the apartments. No flow circulating.</td>
</tr>
</table>

Figure 28 – DHW distribution schemes. Schemes are boolean variables; at every timestep, one and only one of the four schemes has to be active (i.e., equal to 1).

The control of the HP is based on the signals from the sensors in the DHW TES and the HC buffer, which communicate whether the tanks setpoints are satisfied or not.

Due to the distribution system with fan coils, the buffer summer setpoint is fixed to 10-15°C, whereas the winter setpoint is defined with a climatic curve as a function of the outdoor temperature. Supply temperature at the HP load side varies between 30 and 35°C when external temperature is between 15 and 0°C. The priority of the heat pump is always to cover the need for DHW, which depends on the DHW TES temperature.

During summer, the heat pump can recover waste heat for the DHW production. For this reason, the control system also includes an operation mode in which the evaporator side absorbs heat from the water for space cooling and the condenser side transfers heat to the

DHW. This operation is shown in green in Figure 29, which includes all the possible hydronic schemes involving the HP.

The overall control described above, is based on control signals that, in turn, are based on setpoints with hysteresis. The hysteresis upper and lower limits are reported in Table 24.

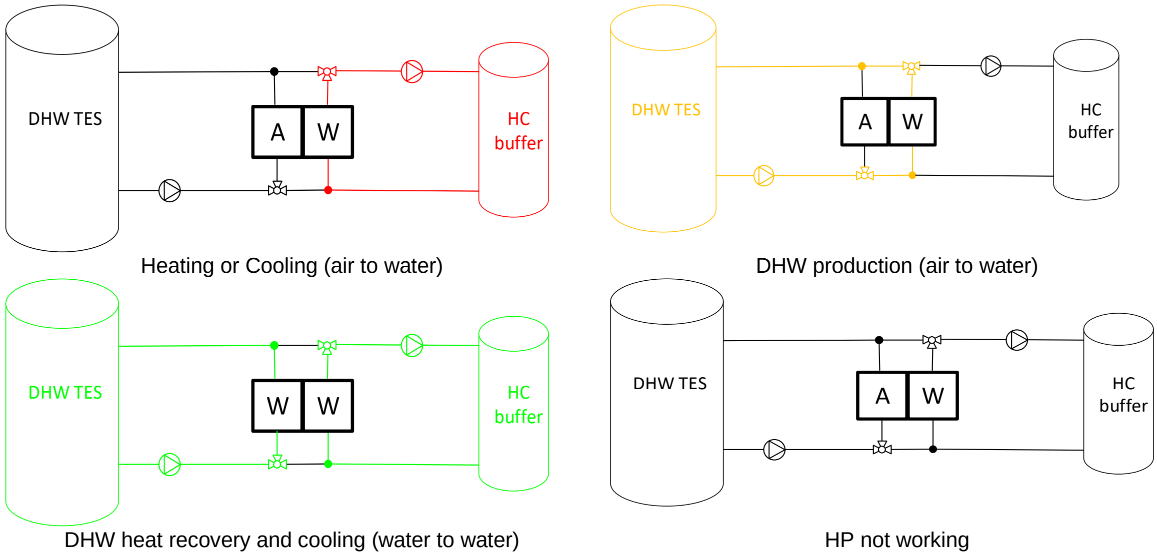


Figure 29 – Operation modes of the heat pump

Table 24 – System control parameters

Ambient winter set point (lower limit – upper limit)	19.75°C–20.25°C
Ambient summer set point (lower limit – upper limit)	24.75*C-25.25°C
Buffer set point for heating climatic curve at Text = 0°C (lower limit – upper limit)	35°C - 40°C
Buffer set point for heating climatic curve at Text = 15°C (lower limit – upper limit)	30°C – 34°C
Buffer set point for cooling (lower limit – upper limit)	10°C – 15°C
DHW TES basic set point (lower limit- upper limit)	48°C – 51°C
DHW TES heat recovery activation hysteresis (lower limit- upper limit)	51°C – 52°C
DHW TES overheat (lower limit- upper limit)	50°C – 53°C
ENERBOXX tank set point (lower limit- upper limit)	45°C – 48°C

The HP is sized with the objective to cover space heating, cooling and DHW demands in all the apartments along the year. The LMFH and the SMFH have different system sizes, as in the SMFH has half of the apartments of the LMFH. However, the sizes that allows to cover the demands are not simply divided by two, since the peak power also depends on other factors, such as the number of the apartments more exposed (the first floor and the top floor) and the level of contemporaneity of the loads. The sizes used in the following study for SMFH and LMFH in the different climates are reported in Table 25.

Table 25 – Sizes of the HP system in the RS3 for the SMFH and the LMFH

	Climate							
	Continental		Oceanic		Mediterranean		Southern Dry	
	Heating	Cooling	Heating	Cooling	Heating	Cooling	Heating	Cooling
SMFH	84 kW	80 kW	84 kW	80 kW	50 kW	48 kW	67 kW	64 kW
LMFH	100 kW	96 kW	100 kW	96 kW	67 kW	64 kW	84 kW	80 kW

3.7.2 Renewable energies

The photovoltaic fields (one for each staircase block) are installed on the building roof, and are made of 36 panels each, with a total power capacity of 10.4 kW (54 kW total power capacity for the whole building). Main characteristics are reported in Table 26. Electricity produced by the photovoltaic field is used for running the heat pump and auxiliaries of the centralized system in the respective staircase.

Table 26 - Photovoltaic field characteristics

Photovoltaic panel	Value
Cell Type	Monocrystalline Silicon
Dimension	1640 mm x 992 mm x 35 mm
Aperture	1.6 m^2
Maximum Power Rating P_n	300 W_p
Module Efficiency	18.4%
Collector slope	10°C
Collector Azimuth	10° South-East
Weight	18 kg

The solar thermal collector field (for the SMFH and for the South staircase in the LMFH) is integrated into the South façade and it is composed by 37 panels. The solar system includes a thermal energy storage to which solar energy is transferred by an internal heat exchanger. The solar collector field, thermal panel and TES characteristics are summarized in Table 27:

Table 27 - Solar field circuit characteristics

Solar collector	Value
Model	VIESSMANN Vitosol 100-FM
Collector aperture area	2.3 m^2
Collector slope	90°C
Collector Azimuth	13° South-East
Collector linear loss coeff.	3.792 W/m^2K
Collector quadratic loss coeff.	0.021 W/m^2K
Optical efficiency	0.824
Solar field	**Value**
Number of single modules in series	4
Number of single modules in parallel	9
Field total area	86,21 m^2
Field capacity	65,12 kW
Number of pump for circulation	2+1
Pump modulation	3 speeds
Mass-flow rate	1 mc/h
Thermal Energy Storage	**Value**
Storage capacity	1500 litres

4 Performance of the studied cases

The presented retrofit solutions have been applied to the reference buildings. Each combination of reference building plus retrofit solution has been evaluated in each climate for a total number of 16 cases.

The choice of combining a solution to a reference case is justified by some considerations that are in the following reported.

RS1 and RS2, that is the decentralized solutions, are not influenced by the shape of the building, but by the load of the single apartment. Considering different apartment shapes in different locations will guarantee the variety of loads. In RS2, the behaviour of the centralized water loop is taken into consideration for a building with a elevate number of floors as geothermal solutions can be assumed to be adopted especially for cases with high number of users. For these reasons, RS 1 and 2 are applied to one reference building only, RS1 to low rise building and RS2 to high rise building. Thanks to the different dwelling sizes and studied climates, the results could give an overview of the retrofit packages energy, environmental and economic performance.

The solution of a centralized system, RS3, is characterized by thermal losses higher than a decentralized system. Plant configuration and control strategies influences this effect, therefore the energy performance of such a system depends on the building typology. Buildings with large extension in width or high, and therefore long pipes, implies higher thermal losses. For this reason, it is suggested to adopt centralized system solution in those building typologies with limited number of floors, or which serves one staircase per time.

Energy, environmental and economic performance of the studied RSs is reported in terms of the influence that intervention on the envelope, HVAC system replacement and use of renewables separately have on the total.

The influence that interventions on the envelope have on the energy consumption is calculated as the energy consumed for covering the building demands after retrofit by using the heating and cooling system of the existing case.

All the comparisons and assessment of energy savings, unless where specified, are calculated with respect to the reference case.

A note for reading the following green graphs that represent how Primary Energy consumption is reduced thanks to the application of the RSs: the light green column represents the Primary Energy consumption of the reference case before any intervention (Reference); the three darker columns indicate how Primary Energy is reduced thanks to the intervention on the envelope (Envelope), to the replacement of the existing HVAC system (Env. + HVAC sys.) and on the use of renewable energies (Env. + HVAC sys. + Renew. En.). Primary Energy after the implementation of the whole RS is therefore represented by the dark green column.

4.1 Case 1 – Low rise building + RS1 in Southern Dry climate

The retrofit package RS1 applied to the low-rise multi-family house can reduce the total primary energy consumption for all the uses with respect to the reference case of 80%. Interventions on the envelope, windows and HVAC system decrease space heating of 82%, space cooling of 42% and DHW (contribution of the HVAC system replacement only) of 28%.

RS1 foresees the coupling of a PV field for each dwelling for reducing the use of electricity. The total primary energy savings, when considering also the contribution of renewable system, amount to around 70-75% for space cooling and DHW production. Influence on space heating is very small, unless advanced control strategy that fosters the exploitation of PV availability is implemented.

By considering the production of electricity from renewable source, the PV self-consumption is 36% that means that one third of the produced energy is directly consumed by the system. This share could be further improved with specific control logics that exploits the renewable energy availability (Figure 30 left).

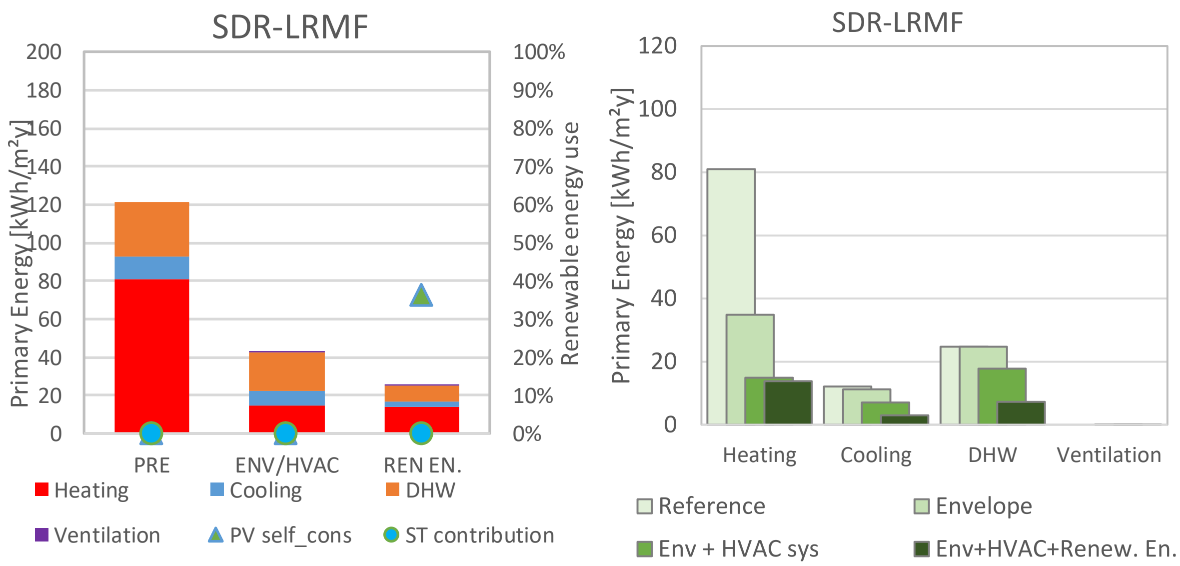


Figure 30 – Primary energy decrease for each applied intervention (left) and primary energy pre intervention, with intervention on the envelope and HVAC system and with renewable energy for all uses (right) for a low rise building in the Southern Dry climate

Looking at the contribution that each intervention on the envelope, HVAC system and renewable energy gives to the consumed primary energy for each use (Figure 30 right), we can observe as insulation of external walls, roof and ground floor plus the replacement of windows reduces energy demand for space heating of more than 50%, while space cooling becomes 8% less. A big contribution to the reduction of the primary energy use is given by the replacement of the existing HVAC system with a more efficient one. With respect to the decrease already obtained with the intervention on the envelope, the replacement of the HVAC system can reduce final consumption for space heating of an additional 25% and for space cooling of 34%. While intervention on the envelope does not influence energy consumption for DHW production, the replacement of the HVAC system reduces the required energy of 28%. Finally, if a PV system is coupled with the Elfo Pack and energy produced is directly consumed by the system, space cooling energy consumption is reduced of an additional 34% and DHW production of 42% thanks to the warming up of water tanks when PV is overproduced.

In the pre retrofit case, mechanical ventilation was not foreseen while in the case post intervention it is included. Despite this additional electricity consumption, the contribution on the total energy consumption can be neglected as ventilation is here meant when there is no space heating or cooling.

Starting from a building primary energy consumption for space heating, cooling, and DHW of 121.5 kWh/m²·y, the installation of the retrofit solution RS1 reduces the primary energy up to 25 kWh/m²·y.

4.2 Case 2 – High rise building + RS2 in Southern Dry climate

Envelope insulation, windows replacement and the use of a decentralized system with ground source heat pumps can reduce the overall Primary Energy consumption for heating, cooling and DHW uses of 47%. While interventions on the envelope and HVAC system are beneficial for heating demand and slightly for DHW production too, cooling consumptions can be significantly reduced thanks to the use of renewable energy only. This effect is due to the large increase of cooling demand after insulating the envelope. The PV self-consumption results to be 14% with therefore a potential increase of this share through the implementation of control strategies that optimize the HVAC system management depending on the PV availability (Figure 31 left).

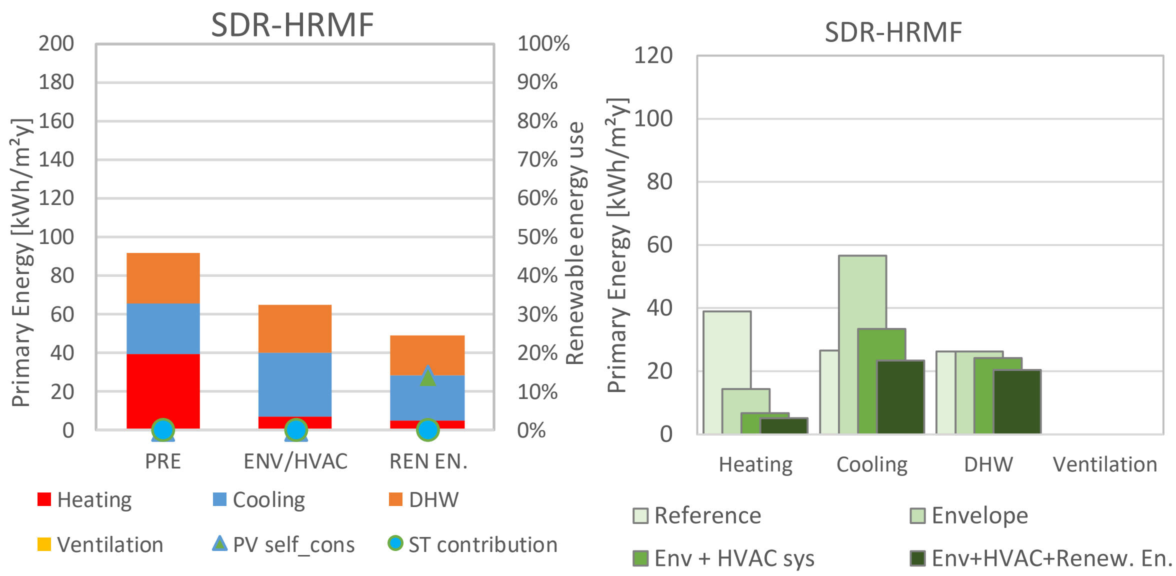


Figure 31 – Primary energy decrease for each applied intervention (left) and primary energy pre intervention, with intervention on the envelope and HVAC system and with renewable energy for all uses (right) for a high rise multi-family house in the Southern Dry climate

The insulation of the envelope for achieving the minimum requirement transmittance reduces of 63% heating demand but strongly increases cooling demand. This effect is due to the building shape factor: dwellings in the intermediate floors have limited thermal losses due to few and small external surfaces and the influence of neighbours. This effect becomes favourable in winter, and in fact heating demand is very low (around 11 kWh/m²y), but results with doubling cooling demands with respect to the case before renovation, becoming 60 kWh/m²y. Thanks to the ground source system that is not influenced by external temperatures, but works with more favourable temperatures of the ground, Primary Energy consumption increase due to the intervention on the envelope is reduced up to only 25% more. The coupling of the decentralized heat pump with a PV field dedicated to each dwelling reduces the total Primary Energy consumption for space cooling of 12% with respect to the case before renovation.

The decrease of heating demand with the envelope insulation and windows replacement is reduced of an additional 20% thanks to the HVAC system and of 4% by the use of the PV field.

In terms of Primary Energy consumption, DHW production is reduced of around 10% by the replacement of the existing HVAC system. This result is due to the electric consumption of the water loop and boreholes, in addition to the consumption of the heat pump that works with lower COPs due to the high supply temperature for DHW production. Also in this case, the PV field gives a contribution up to achieve a total PE consumption saving for DHW production of 22%.

The high rise multi-family house located in a Southern Dry climates reduces Primary Energy consumption of 92 kWh/m²y up to 49 kWh/m²y thanks to the adoption of RS2 (Figure 31 right).

4.3 Case 3 – Small MFH + RS3 in Southern Dry climate

The installation of RS3 to a small MFH located in the Southern Dry climate can reduce the consumption of Primary Energy for space heating, space cooling, DHW production and mechanical ventilation of 73%. Specifically, the envelope insulation and replacement of windows and HVAC system cuts energy consumption of 70% for heating, 60% for cooling and 85% for DHW. The contribution of solar technologies, both PV installed on the roof and ST collectors, results on a total PE consumption reduction of 70-77% for space heating and cooling and 87 for DHW.

Thanks to the climate conditions, solar thermal contribution amounts to 21%, while PV self-consumption is 18%. Specific control logics could increase the share of PV use (Figure 32 left).

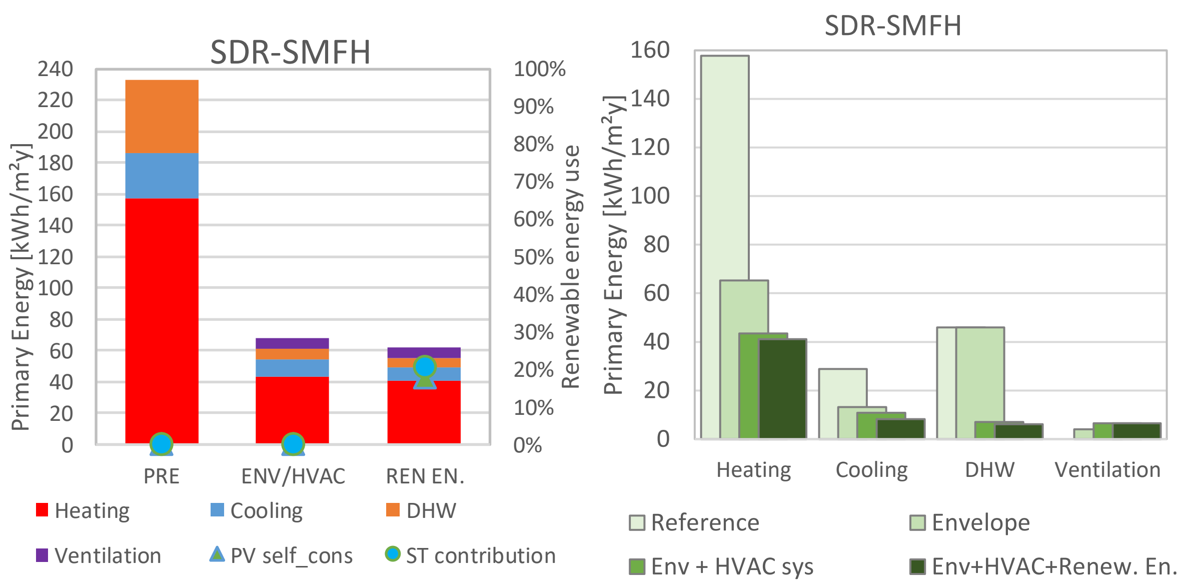


Figure 32 – Primary energy decrease for each applied intervention (left) and primary energy pre intervention, with intervention on the envelope and HVAC system and with renewable energy for all uses (right) for a small multi-family house in the Southern Dry climate

Envelope insulation and windows replacements halve the demand for space cooling and reduce heating demand of 60%. To this, enhancing also the HVAC system with the solution proposed in RS3, an additional 14% for heating and 8% for cooling is achieved on top of the previous savings. DHW production benefits of 85% reduction of PE consumption. RS3 contains the use of solar thermal collectors and PV panels that contributes for an additional reduction of Primary Energy consumption of 9% for space cooling and 2% for DHW (see Figure 32 right).

The analysed retrofit solution entails a consumption of energy for mechanical ventilation in the order of 3 kWh/m²y, that, together with the savings achieved with the other intervention, does not affect considerably the final energy consumption. The Primary Energy consumption of the reference case assessed to 233 kWh/m² is reduced to 62 kWh/m²y thanks to the implementation of RS3.

4.4 Case 4 – Large MFH + RS3 in Southern Dry climate

The retrofit package RS3 applied to the large multi-family house located in the Southern Dry climate can reduce the total primary energy for all the uses of 72%. The main reduction (equal to 80%) is observed for space heating thanks to envelope insultation, windows replacement and HVAC system enhancement, while energy savings for DHW amounts to 70% thanks to the HVAC system enhancement. Space cooling primary energy consumption is reduced by 43%. By considering the contribution of renewable, energy savings for space heating, space cooling and DHW amount to 81%, 58% and 73% respectively with respect to the reference case.

Due to the small available area for PV installation with respect to the building area, the PV self consumption is 40% while the ST contribution is 4%. The high ratio of PV self consumption is due to the high load with respect to the installed PV power. On the contrary, the ST contribution is low as the installed area is small with respect to the number of dwellings (Figure 33 left).

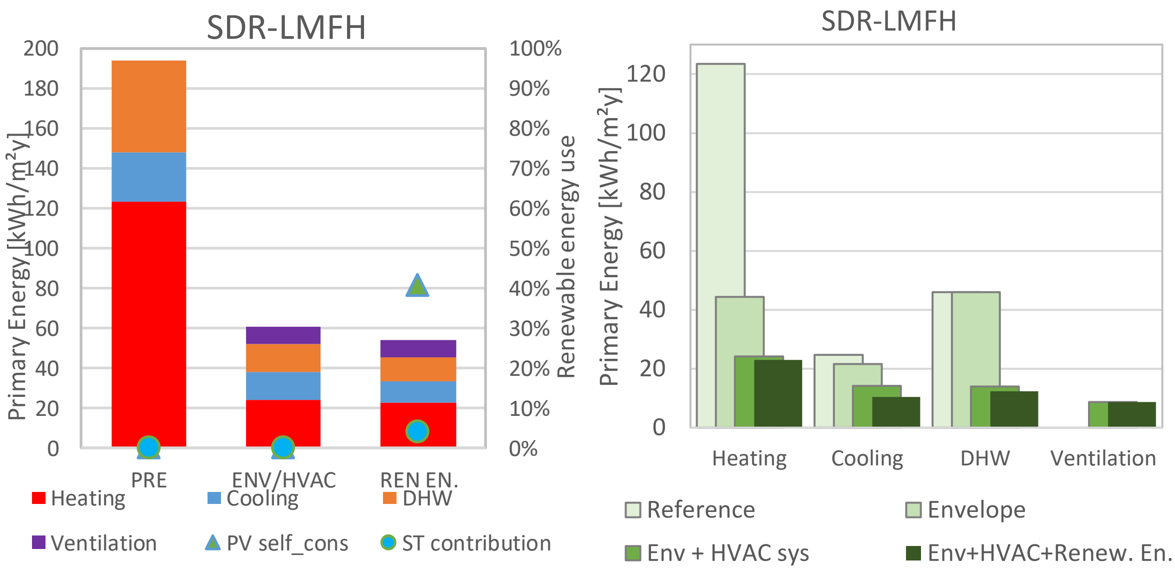


Figure 33 – Primary energy decrease for each applied intervention (left) and primary energy pre intervention, with intervention on the envelope and HVAC system and with renewable energy for all uses (right) for a large multi-family house in the Southern Dry climate

Looking at the contribution that each intervention on the envelope, HVAC system and renewable energy gives to the primary energy consumed for each use (Figure 33 right), we can observe as insulation of external walls, roof and ground floor plus the replacement of windows reduces energy demand for space heating of more than 60% and for space cooling of 12%. A big contribution to the reduction of the final energy use is given by the replacement of the existing HVAC system with a more efficient one. With respect to the decrease already obtained with the intervention on the envelope, the replacement of the HVAC system can reduce final consumption for space heating for an additional 16% and for space cooling of 30%. While intervention on the envelope does not influence energy consumption for DHW production, the replacement of an electric boiler with a centralized heat pump system reduces up to 70% the required energy for covering this use. Finally, a PV system installed on the roof contributes to the reduction of electricity for the centralized system, apporting energy savings for heating production of an additional 1%, for cooling of 15% and for DHW of an additional 3%.

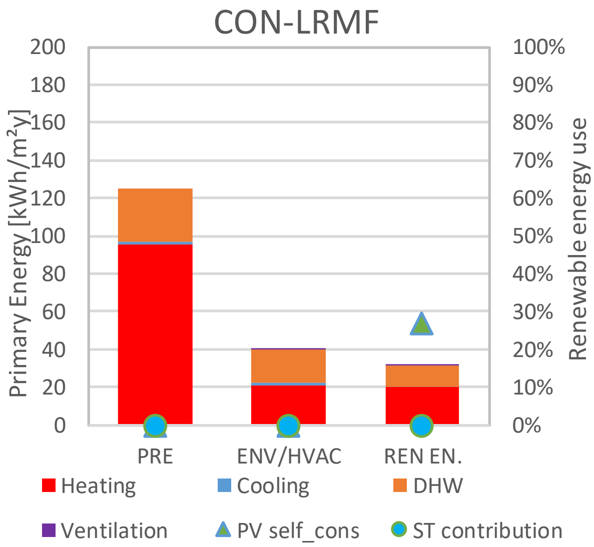
In the case pre retrofit, mechanical ventilation was not foreseen while in the case post intervention is included. Despite this additional electricity consumption, the total primary energy consumption post retrofit is much less than pre-retrofit.

Starting from a building consumption for space heating, cooling, and DHW of 194 kWh/m²·y, the installation of the retrofit solution RS3 reduces the final energy to 54 kWh/m²·y.

4.5 Case 5 – Low rise building + RS1 in Continental climate

In the Continental Climate, demand for space cooling is almost zero, therefore the main contributions for energy consumption are for space heating and DHW production. The application of RS1 to the low-rise building in the Continental climate contributes to the reduction of the total primary energy consumption for all uses with respect to the case before intervention of 75%. The insulation of the building plus the replacement of the windows and HVAC system with the Elfo pack reduces primary energy consumption for space heating of 78%, for space cooling of 29% and for DHW production of 37%.

By considering the contribution that the PV field gives to the total energy consumption, primary energy is reduced of 1% for space heating, up to 68% for space cooling and up to 60% for DHW. Due to the climate, space cooling is very low therefore although the savings in relative terms are quite relevant, in absolute terms they result on around 1 kWh/m²y. The rate of self-consumption for the produced energy by PV amounts to 27% (Figure 34 left).



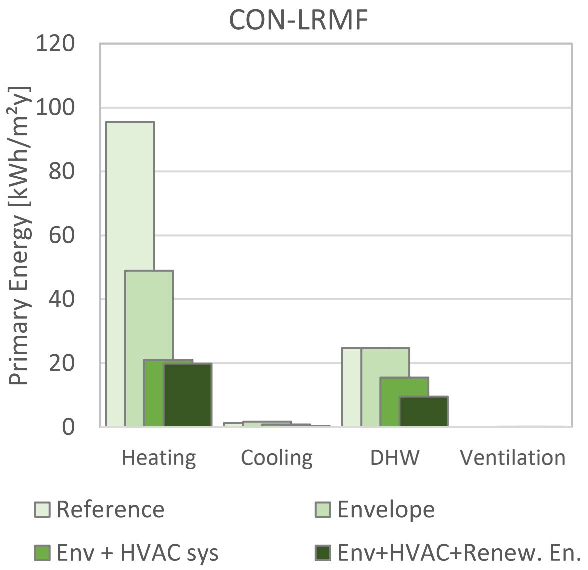


Figure 34 – Primary energy decrease for each applied intervention (left) and primary energy pre intervention, with intervention on the envelope and HVAC system and with renewable energy for all uses (right) for a low rise building in the Continental climate

The intervention on the envelope and the replacement of the existing windows halves the heating demand, while space cooling increases of 45% although in absolute terms the increase is less than 1 kWh/m²y. Thanks to the installation of a decentralized solution of heat pump plus mechanical ventilation, energy for covering space heating demand is reduced of an additional 30%, energy for space cooling decreases of 30% from the case before intervention by eliminating the increase od demand and energy for DHW production is reduced by 37%. The use of a PV system coupled with the Elfo Pack can decrease the primary energy consumption of an additional 24% for DHW production and 39% for space cooling (Figure 34 right).

The low-rise building in the Continental climate pre-intervention showed a total primary energy consumption of 125 kWh/m²y. Thanks to the implementation of RS1, total primary energy consumption amounts to 31 kWh/m²y.

4.6 Case 6 – High rise building + RS2 in Continental climate

The installation of RS2 to a high-rise multi-family house located in a Continental climate is able to reduce Primary Energy consumption for space heating, cooling and DHW production of 60%. The main reduction is obtained by insulating the envelope and replacing the windows and the HVAC system with a decentralized ground source heat pumps system in the order of 76% for space heating, 13% for space cooling and 6% for DHW production. An additional contribution is given by the coupling of the heat pump with a PV system whose self-consumption results 12% (Figure 35 left).

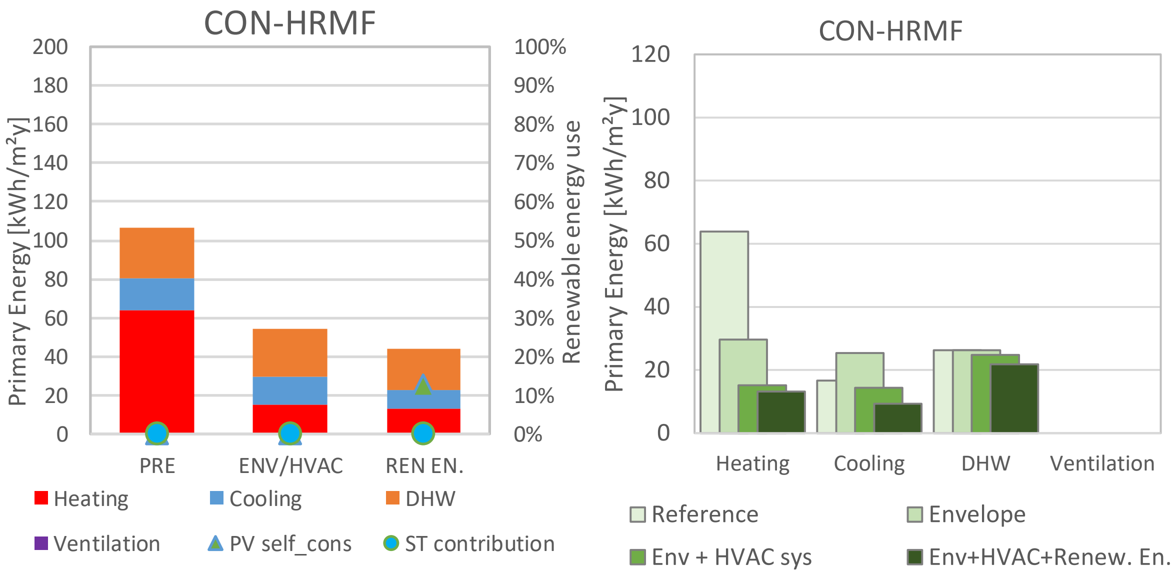


Figure 35 – Primary energy decrease for each applied intervention (left) and primary energy pre intervention, with intervention on the envelope and HVAC system and with renewable energy for all uses (right) for a high rise multi-family house in the Continental climate

Looking more in detail how RS2 influences building consumption (Figure 35 right), the envelope insulation and the replacement of the windows halve heating demand but almost double cooling demand. Thanks to the adoption of ground source heat pumps that work with high efficiency thanks to the more favorable ground temperatures, Primary Energy consumption with respect of the case without RS2 is reduced of 75% for space heating, 13% for space cooling and 6% for DHW production. The coupling of the heat pump with a PV field per dwelling contributes with an additional PE consumption reduction of 3% foe space heating, 30% for space cooling and 11% for DHW uses.

Primary Energy consumption for a high-rise building located in the Continental climate can reduce from 107 kWh/m²y to 44 kWh/m²y thanks to the adoption of RS2.

4.7 Case 7 – Small MFH + RS3 in Continental climate

The Continental climate is characterized by cold winters and mild summers. For this reason, the insulation of the envelope and the replacement of the windows, together with the change of the HVAC system, almost cancel the consumption for space cooling, while space heating consumption is reduced by 60% and DHW by 70%. The contribution of renewable energy slightly improves these savings up to achieve a total Primary energy consumption of 61%. In this case, PV self-consumption and solar thermal contribution amount both to 11% (Figure 36 left).

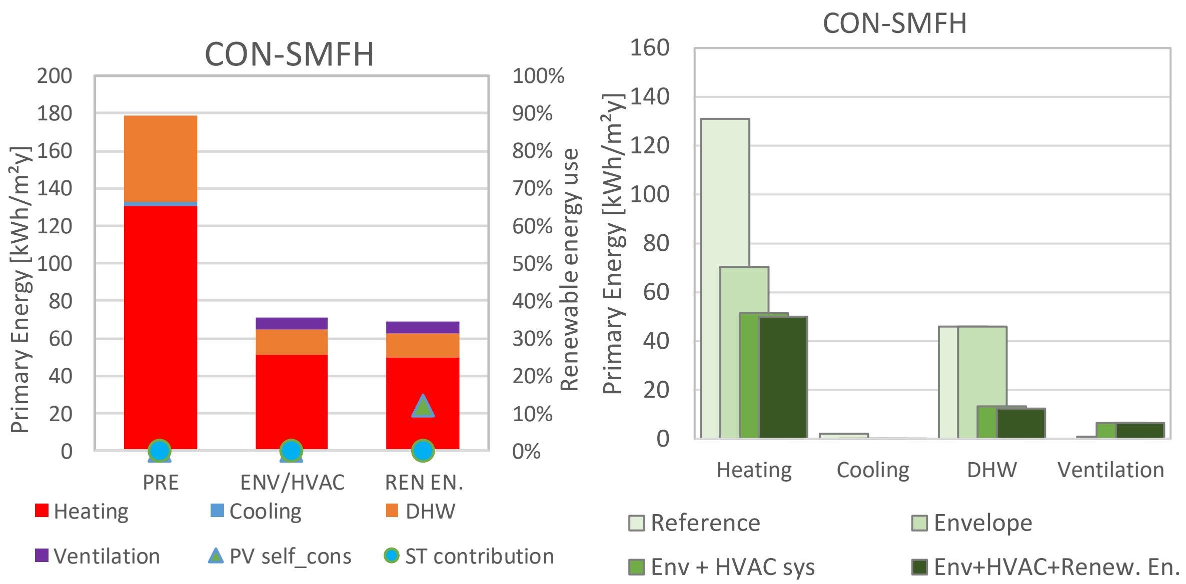


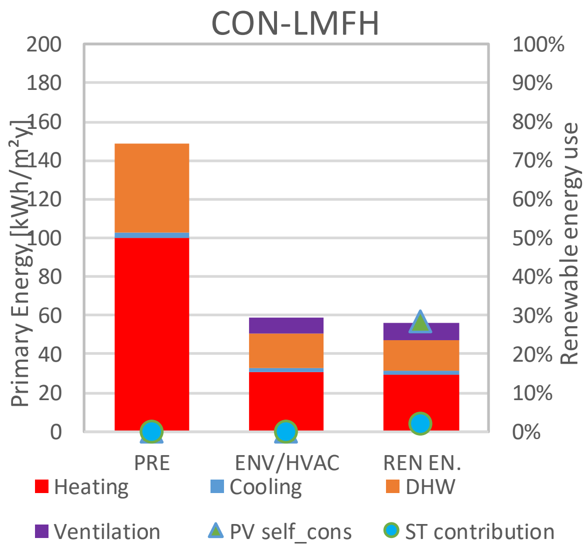
Figure 36 – Primary energy decrease for each applied intervention (left) and primary energy pre intervention, with intervention on the envelope and HVAC system and with renewable energy for all uses (right) for a small multi-family house in the Continental climate

Considering the effect of each intervention on the single uses, intervention on the envelope almost halves the demand of heating and cancel the demand for space cooling. A centralized system with heat pump increases Primary Energy savings for space heating of an additional 14% with respect to the reference case and of 70% for DHW production. As already seen, renewable energy technologies have a small impact, in the order of 1-2% of total energy savings, due to the climatic conditions (Figure 36 right).

The implementation of RS3 in a small multi-family house located in a Continental climate is able to reduce Primary Energy consumption for space heating, space cooling, DHW production and mechanical ventilation from 179 kWh/m²y to 69 kWh/m²y.

4.8 Case 8 – Large MFH + RS3 in Continental climate

The retrofit package RS3 applied to the large multi family house Continental climate can reduce the total primary energy for all the uses of 62%. Interventions on the envelope and replacement of the HVAC system reduce primary energy consumption for space heating, cooling and DHW of 70%, 8% and 62% respectively. The coupling of a PV system and ST system further reduces primary energy consumption up to achieve total savings of one third for space cooling and 65% for DHW production. The PV self-consumption amounts to 28% of the total PV production while the ST contribution amounts to 2%. For this value, to be considered that the whole heating production (space heating + DHW) and the whole building (five staircases) are considered although the system is installed on the south façade only and covers only DHW needs (see Figure 37 left).



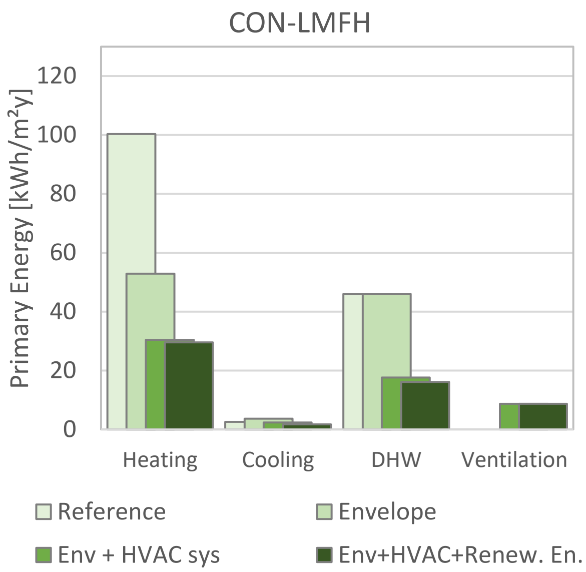


Figure 37 – Primary energy decrease for each applied intervention (left) and primary energy pre intervention, with intervention on the envelope and HVAC system and with renewable energy for all uses (right) for a large multi-family house in the Continental climate

Looking at each intervention of the RS3, envelope insulation and windows replacement can reduce space heating of 47% while space cooling increases. In relative terms this increase is of 40% but in absolute terms it is 1 kWh/m² due to the low cooling loads of this climate.

However, the replacement of the HVAC system and enhancement of its performance halves primary energy consumption for space cooling and reduces of an additional 22% energy consumption for space heating and of 62% energy for DHW production. The contribution of a PV and ST systems bring an addition 27% savings for space cooling and 3% for DHW (see Figure 37 right).

The initial primary energy consumption of the large-MFH in the Continental climate of 149 kWh/m²y is reduced through the application of RS3 up to 56 kWh/m²y despite the additional energy consumption due to a slight increase of cooling demand and the presence of a mechanical ventilation system.

4.9 Case 9 – Low rise building + RS1 in Oceanic climate

In the Oceanic climate, the main energy uses are for covering space heating and DHW production as space cooling demand is very low, below 5 kWh/m²y. The installation of RS1 to the low-rise building can reduce primary energy consumption of 85% for covering heating demand and 40% for DHW demand. If also the contribution of PV is considered, savings amount to around 78% for cooling and 60% for DHW. The PV self-consumption results 22% (see Figure 38 left).

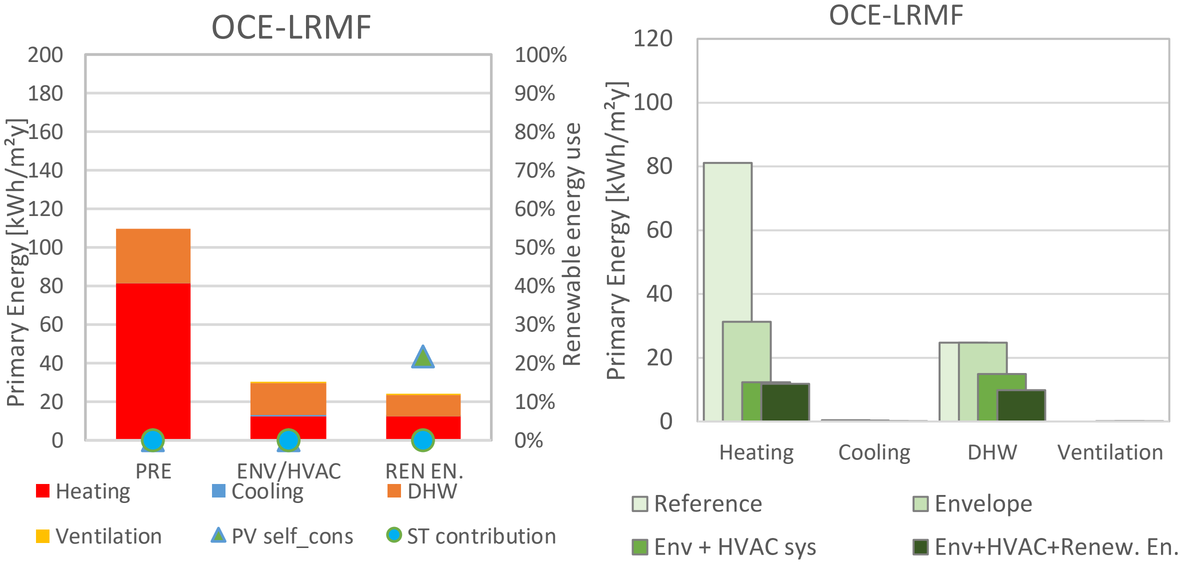


Figure 38 – Primary energy decrease for each applied intervention (left) and primary energy pre intervention, with intervention on the envelope and HVAC system and with renewable energy for all uses (right) for a low rise building in the Oceanic climate

Interventions on the envelope reduces of 60% the heating demand. The replacement of the existing HVAC system with a decentralized heat pump plus mechanical ventilation contributes to an additional energy saving for space heating of 23% and for DHW production of 40%. The coupling of the heat pump with a PV system brings additional primary energy consumption savings for space heating of 1%, but for DHW production of 20% (see Figure 38 right).

The low rise building before intervention has a total primary energy consumption of almost 110 kWh/m²y that, thanks to the implementation of the RS1, is reduced to 23 kWh/m²y.

4.10 Case 10 – High rise building + RS2 in Oceanic climate

A high rise building located in the Oceanic climate can reduce of 63% its Primary Energy consumption thanks to the adoption of RS2. While consumption for heating demand is strongly cut off thanks to the reduction of thermal losses and the use of an efficient energy system, space cooling, usually very low in this location, increases. In absolute terms, space cooling consumption increase is very small, in the order of 3 kWh/m²y although in relative terms becomes almost 4 times higher.

The adoption of an efficient HVAC system contributes to slightly reduce also Primary Energy consumption for DHW too, reduction that achieves almost 20% with the use of a PV system (see Figure 39 left).

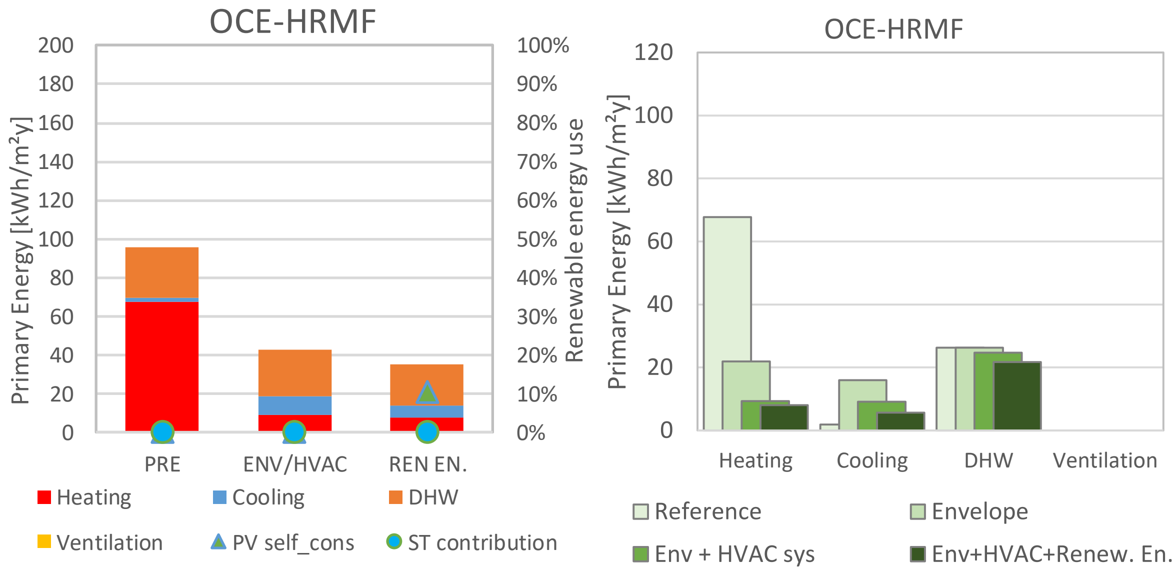


Figure 39 – Primary energy decrease for each applied intervention (left) and primary energy pre intervention, with intervention on the envelope and HVAC system and with renewable energy for all uses (right) for a high rise multi-family house in the Oceanic climate

Due to the building typology, almost all the dwellings have low thermal losses due to the few external surfaces. The insulation of the envelope and the replacement of the windows contribute to reduce space heating (68%) and increase space cooling. Despite the adoption of an efficient HVAC system, Primary Energy consumption for space cooling cannot be reduced with respect to the case without RS2. However, the new interventions act on the reduction of consumption for space heating and DHW that represent the higher loads. Heating demand primary energy consumption is cut off of 80% and DHW PE consumption of 18%, included the contribution of the PV field (Figure 39 right).

Primary Energy consumption of a high rise building located in the Oceanic climate is reduces from 96 kWh/m²y to 35 kWh/m²y thanks to the implementation of RS2.

4.11 Case 11 – Small MFH + RS3 in Oceanic climate

RS3 applied to a small MFH located in a Oceanic climate can reduce Primary Energy consumption for all the uses up to 71%. Due to the mild summers, energy consumption for space cooling is null, therefore it will be not considered in the following. Interventions on the envelope and HVAC system replacement reduce energy consumption for space heating of 74% and for DHW production of 70%.

PV and ST fields contribute on a reduction of Primary Energy consumption for an additional 1 to 3% resulting with a PV self-consumption of 9% and ST contribution of 12% (Figure 40 left).

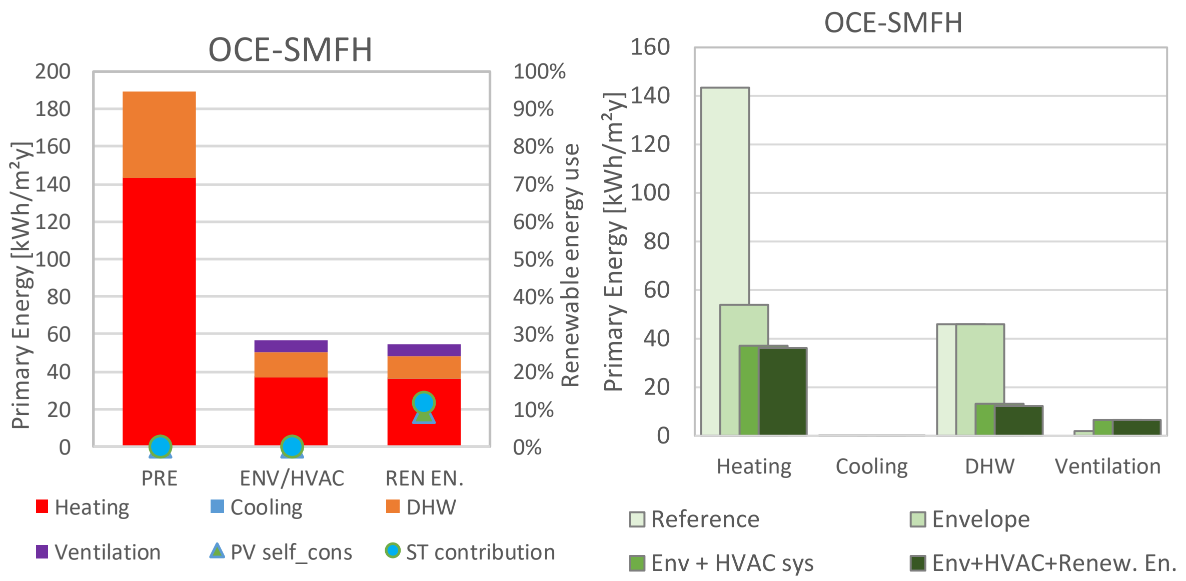


Figure 40 – Primary energy pre intervention, with intervention on the envelope and HVAC system and with renewable energy for all uses (left) and primary energy decrease for each applied intervention (right) for a small multi-family house in the Oceanic climate

More in detail, energy reduction for space heating are due for 62% of the reference case to the intervention on the envelope and for 12% of the reference case on the HVAC system replacement. The centralized heat pump-based system reduces of 70% Primary Energy consumption for DHW production with an electric boiler without changing the user demand (Figure 40 right).

RS3 to a small multi-family house located in the Oceanic climate is able to reduce Primary Energy consumption of a reference case from 189 kWh/m²y to 55 kWh/m²y.

4.12 Case 12 – Large MFH + RS3 in Oceanic climate

The application of RS3 on a large MFH located in the Oceanic climate has an important effect around 80% on the energy consumed for space heating and of 66% on the DHW uses. Space cooling slightly increases but the total primary energy consumption is assessed to be lower than 1 kWh/m² due to the climate conditions. The coupling of centralized PV and ST systems reduces energy consumption for DHW up to 6% achieving a PV self-consumption of 23% and ST contribution on the whole building of 2% (see Figure 41 left).

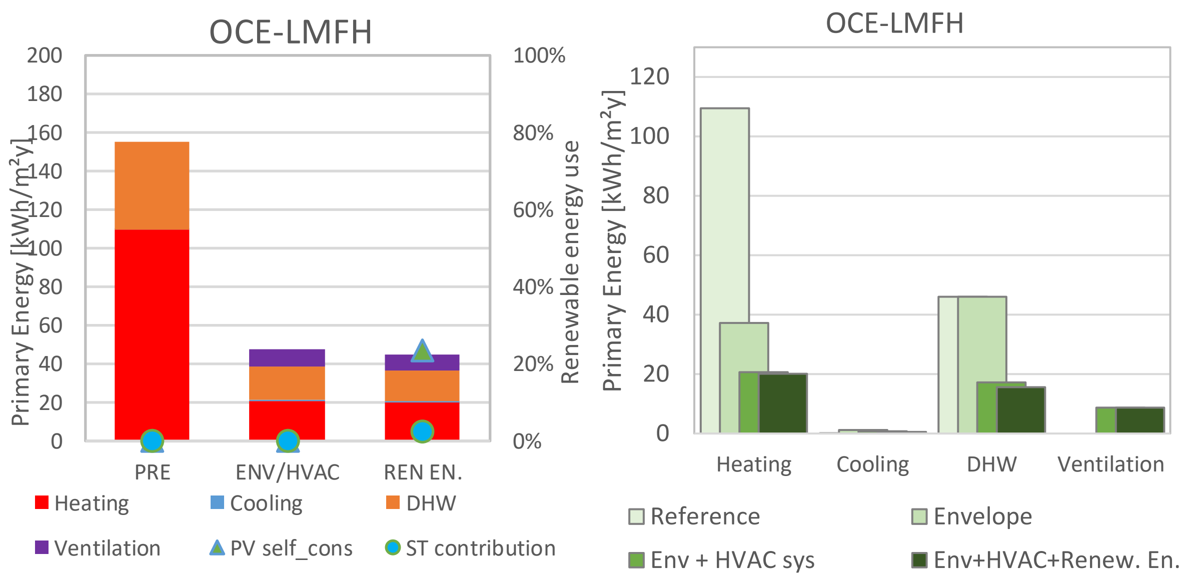


Figure 41 – Primary energy decrease for each applied intervention (left) and primary energy pre intervention, with intervention on the envelope and HVAC system and with renewable energy for all uses (right) for a large multi-family house in the Oceanic climate

Envelope insulation and windows replacement reduces space heating primary energy consumption of 66%. The HVAC system enhancement contributes with additional savings of 15%, while reduces consumption for DHW production of 63%.

Together with the use of renewable energy, the total primary energy savings that can be achieved by applying RS3 to a large MFH in the Oceanic climate is 82% for space heating and 66% for DHW. The initial Primary Energy consumption pre retrofit of 155 kWh/m²y is therefore reduced up to 45 kWh/m², included the uses for space cooling and mechanical ventilation (see Figure 41 right).

4.13 Case 13 – Low rise building + RS1 in Mediterranean climate

For the configuration of the building typology with overhangs and balconies, solar gains and consequently cooling demand are not high. Despite that, the low rise building in the Mediterranean climate presents, in addition to space heating and DHW, some space cooling demand. The application of RS1 to the low rise building in the Mediterranean climate can reduce the total energy consumption for all the uses of 83%. In particular, the implementation of the insulation on the envelope, new windows and a more efficient HVAC system reduce energy consumption for space heating of 90%, for space cooling of 40% and for DHW production of 28%. The coupling of the machine with a PV system allows to achieve Primary Energy savings of 70-75 % for space cooling and DHW production. Thanks to the high solar radiation and the simultaneity of cooling demand with PV production, the PV self consumption on yearly basis amounts to 33% (Figure 42 left).

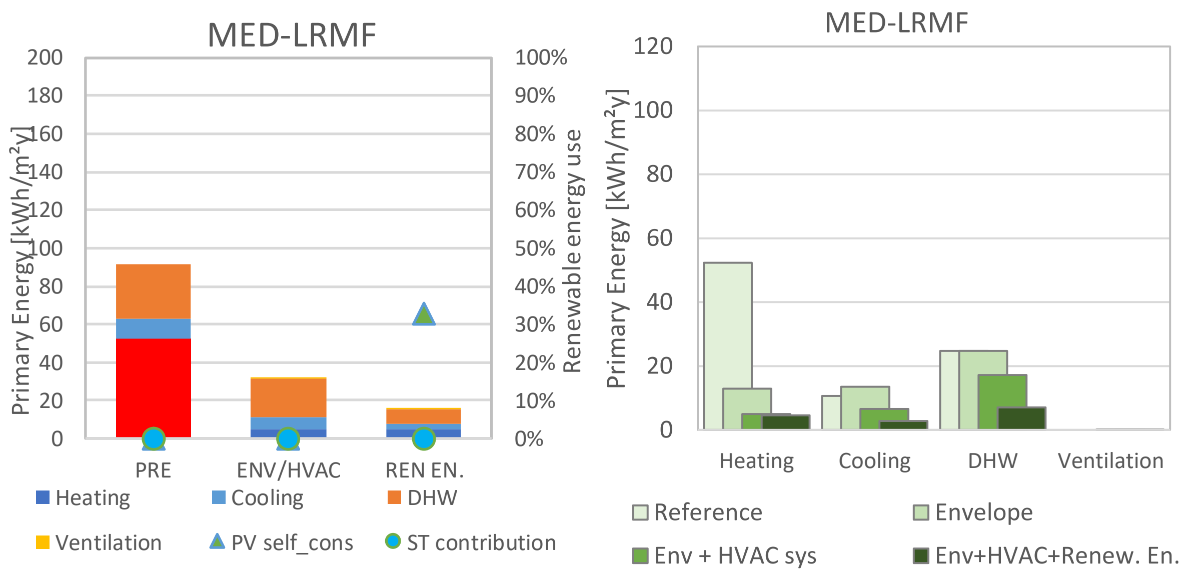


Figure 42 – Primary energy decrease for each applied intervention (left) and primary energy pre intervention, with intervention on the envelope and HVAC system and with renewable energy for all uses (right) for a low rise building in the Mediterranean climate

Due to the restrictive requirements for energy renovation, the intervention on the envelope and the replacement of the windows reduces the space heating up to one quarter. The high insulation level brings an increase of space cooling in the order of 27% that, in absolute terms, changes from 11.6 to 14.7 kWh/m²y (Figure 42 right).

The adoption of a decentralized system able to cover space heating, space cooling, DHW production and mechanical ventilation reduces energy consumption of the building with interventions on the envelope of an additional 15% for space heating, 66% for space cooling and 30% for DHW production. Energy consumed by mechanical ventilation represents less than 0.5% of the total energy consumption.

The coupling of a PV system to the Elfo Pack contributes with an additional energy reduction of 36% for space cooling and 40% for DHW production (Figure 42 right).

The existing low-rise building located in the Mediterranean climate has a total primary energy consumption for all the uses of 91 kWh/m²y that with the application of RS1 decreases to 16 kWh/m²y.

4.14 Case 14 – High rise building + RS2 in Mediterranean climate

A high rise multi-family house located in the Mediterranean climate and built in 1980-1990 can reduce Primary Energy consumption for space heating, space cooling and DHW production of 42% thanks to the adoption of RS2. The level of the achieved savings depends on the implemented measures but also on the starting point. A building with the characteristics of the reference case presents low heating demand (around 20 kWh/m²y) due to the initial transmittance values and shape of the building. Cooling demand is of the same order (around 25 kWh/m²y). The implementation of the renovation measures on the envelope for achieving the minimum requirements has as consequence the reduction of space heating up to 6 kWh/m²y and the increase of cooling demand up to 60 kWh/m²y. As a consequence, Primary Energy consumption for space heating is reduced of 88% from the reference to the case with RS2, while PR consumption for space cooling increases of 38%. Thanks to the coupling of the heat pump with a PV system per dwelling, the final PE consumption for space cooling results reduced of 11%, while for DHW of 23%. PV self-consumption is 15% as the use of solar energy is accounted when simultaneous to energy consumption and any control strategies that exploits PV availability is considered (Figure 43 left).

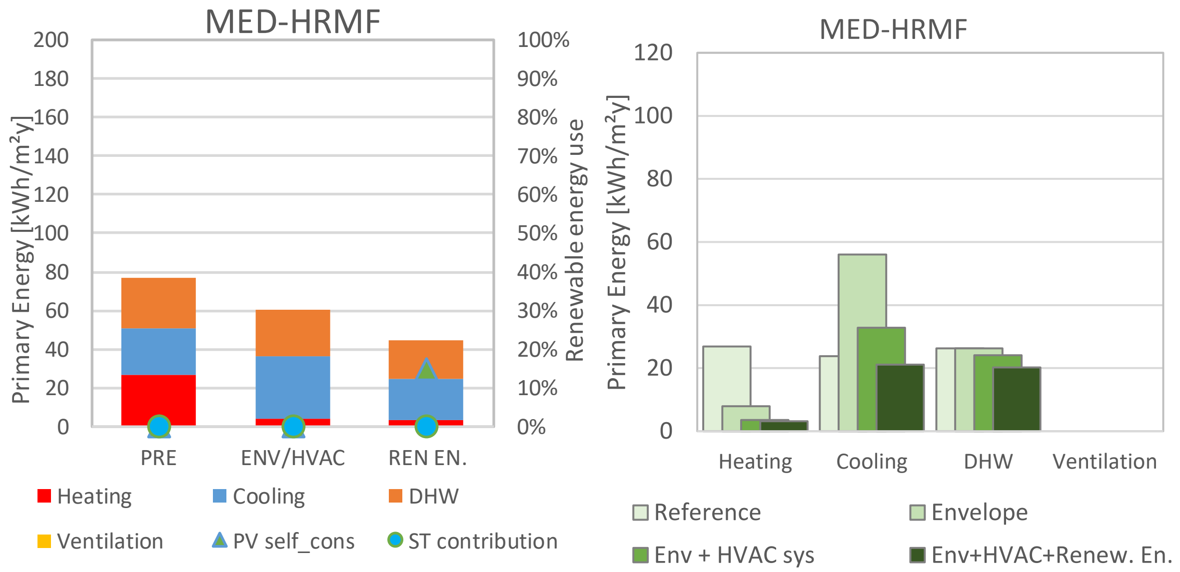


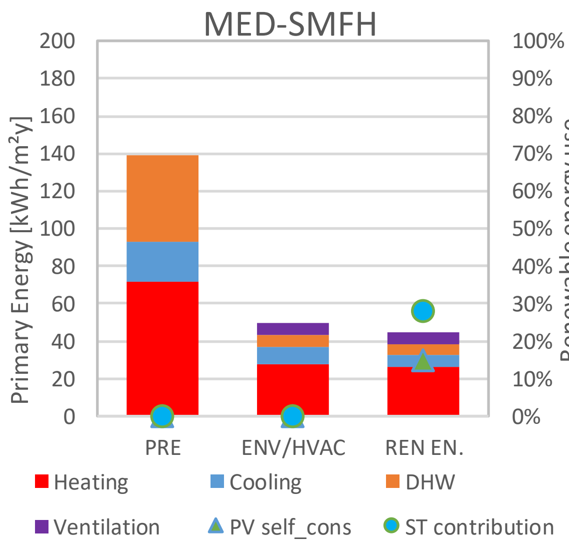
Figure 43 – Primary energy decrease for each applied intervention (left) and primary energy pre intervention, with intervention on the envelope and HVAC system and with renewable energy for all uses (right) for a high rise multi-family house in the Mediterranean climate

As mentioned, envelope insulation and replacement of the windows cut Primary Energy consumption for space heating of 70% that, together with the implementation of a decentralized ground source heat pump achieves 87%. On the contrary, space cooling strongly increases with the intervention on the envelope. The additional Primary Energy use is in part compensated by an efficient HVAC system up to register an increase of 38%. Primary Energy for DHW production is reduced of 8% with the new HVAC system and of an additional 15% when coupled with the PV system. The use of renewable energy helps to obtain positive energy savings on the space cooling too (Figure 43 right).

Primary Energy consumption of 77kWh/m²y of the reference high rise building located in the Mediterranean climate is reduced up to 44 kWh/m²y thanks to the adoption of the RS2.

4.15 Case 15 – Small MFH + RS3 in Mediterranean climate

The application of a centralized system with heat pump in a small multi-family house located in the Mediterranean climate can reduce the consumption of Primary Energy for space heating, cooling, DHW production and mechanical ventilation of 68%. Envelope insulation plus replacement of windows and HVAC system cut PE consumption of around 60% for space heating and space cooling and of 86% for DHW needs. Thanks to the climatic conditions, RS3 can exploit solar energy with the effect of reducing energy consumption for these uses up to 70-74% for space cooling and heating and 87% for DHW production. PV self-consumption in this case amounts to 15% and solar thermal contribution to 28% (Figure 44 left).



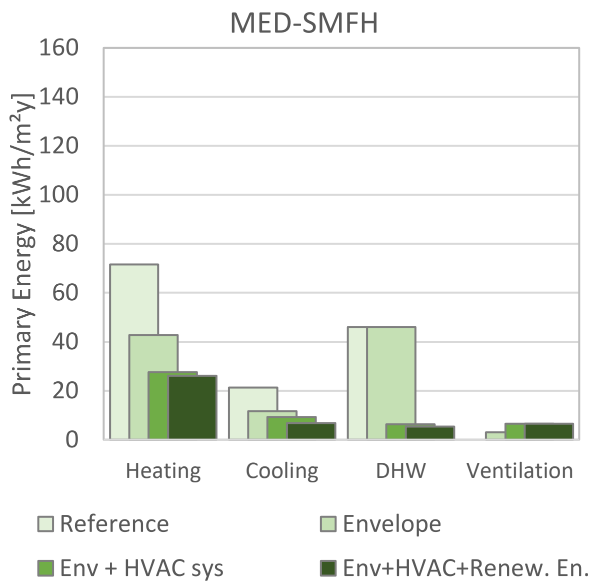


Figure 44 – Primary energy decrease for each applied intervention (left) and primary energy pre intervention, with intervention on the envelope and HVAC system and with renewable energy for all uses (right) for a small multi-family house in the Mediterranean climate

The insulation of the envelope and the replacement of the windows cut energy demand for heating and cooling of 40% and 46%, while the enhancement of the HVAC system contributes with an additional 21% for heating and 11% for cooling of Primary Energy savings. The new system strongly decreases PE consumption for DHW up to 86%.

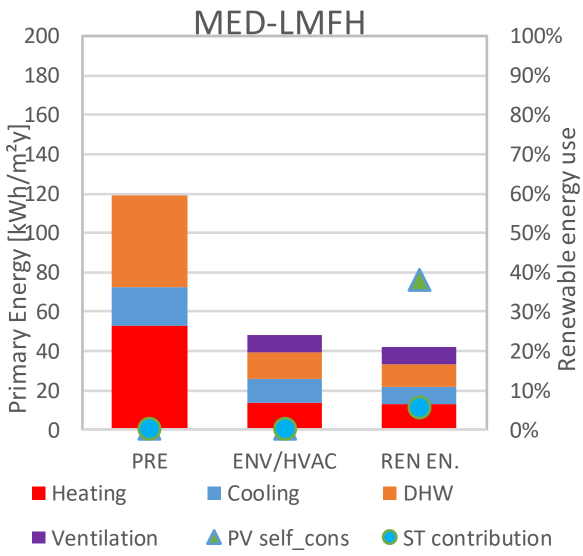
The contribution of renewable energies on the Primary energy consumption amounts to an additional 2% for space heating and DHW and 11% for space cooling with respect to the reference case (Figure 44 right).

RS3 applied to a small MFH located in the Mediterranean climate can reduce Primary Energy consumption for all the uses, mechanical ventilation included, from 139 kWh/m²y to 45 kWh/m²y.

4.16 Case 16 – Large MFH + RS3 in Mediterranean climate

The application of RS3 to a large MFH located in the Mediterranean climate is able to reduce primary energy consumption for space heating of around 75%, for space cooling of 37% and for DHW production of 70%. The use of a PV field and solar thermal collectors contributes to reduce up to 55% the consumption for space cooling and 75% for DHW production.

Due to the higher solar radiation of southern climates, in this case PV self-consumption amounts to 38% and solar contribution on the building total heating production to 5% (see Figure 45 left).



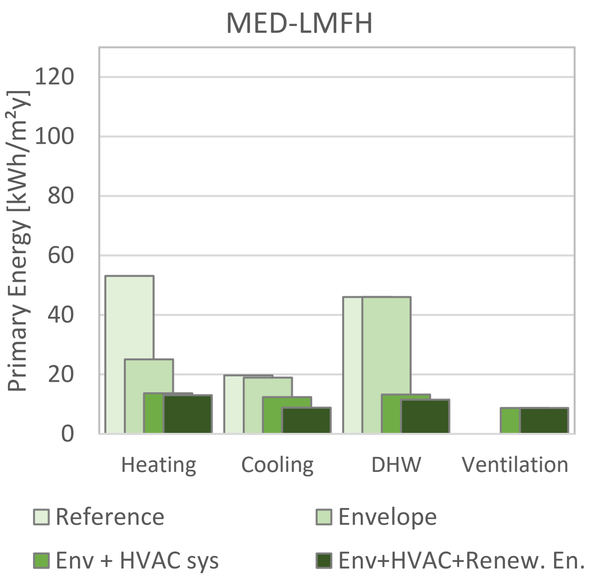


Figure 45 – Primary energy decrease for each applied intervention (left) and primary energy pre intervention, with intervention on the envelope and HVAC system and with renewable energy for all uses (right) for a large multi-family house in the Mediterranean climate

Insulation of the envelope following the local requirements and the replacement of the windows reduces the Primary Energy consumption for space heating of 53% while for space cooling of 4%. Higher thermal capacity of a building results with higher cooling demand but the use of windows with better performance can minimize this effect.

A centralized system for the production of heating, cooling and DHW can contribute with an important reduction of primary energy consumption for these uses. In particular, energy for space heating is reduced of and addition 21%, energy for space cooling is one third less and energy for DHW is 70% less.

Thanks to the high solar radiation and the presence of a PV and ST system, space cooling consumption see an additional reduction of 18% and DHW of 4%. PV can reduce energy consumption for space heating of only 1%.

Considering all the interventions of RS3 on a large MFH located in the Mediterranean climate, Primary energy consumption pre renovation for all the uses of 119 kWh/m²y is reduced up to 42 kWh/m²y. this quantity considers also electricity used by the mechanical ventilation that was not present in the reference case (see Figure 45 right).

5 Discussion on Retrofit protocols performance

5.1 Retrofit packages energy and environmental performance

5.1.1 Intervention on the envelope

The proposed retrofit packages aim at covering the most common renovation solutions in different multi-family house typologies and climates throughout Europe. Due to the variety of building typologies and studied renovation solutions, a comparison between the different cases is not straightforward. However, some energy, environmental and economic considerations can be reported.

The proposed retrofit packages promote energy savings by reducing the building energy demands, by improving the energy plant efficiency and by adopting renewable energies.

Interventions on the envelope are defined based on the minimum transmittance requirements defined by countries when refurbishing a building. This means that for each country, the target external surfaces performance is the same regardless the building typology. Figure 46 shows in the bars the specific Final electric energy consumption for all the studied cases while the dots indicate energy demand for space heating, space cooling and DHW. DHW demand per square meter has been supposed to be the same for all the climates and buildings. While Final energy depends on the system efficiency, energy demand is strictly related to the building shape and thermal characteristics. Figure 46 shows as, having same external surfaces thermal transmittance, the building shape factor and the use of the building influence heating demand for 60-80% depending on the climate and varying from the high-rise building to the small multi-family house by 30 kWh/m²·y in the Oceanic climate, 24 kWh/m²·y in the Continental, 27 kWh/m²·y in the Mediterranean and 39 kWh/m²·y in the Southern Dry. The difference between the different building typologies for space cooling is instead higher than for space heating due to the decrease of walls transmittance and replacement of windows that strongly reduces thermal losses. As a consequence, space cooling from the building with the lowest S/V ratio and the one with the highest varies of 27 kWh/m²·y in the Oceanic climate, 17 kWh/m²·y in the Continental, and almost 50 kWh/m²·y in Mediterranean and Southern Dry climates.

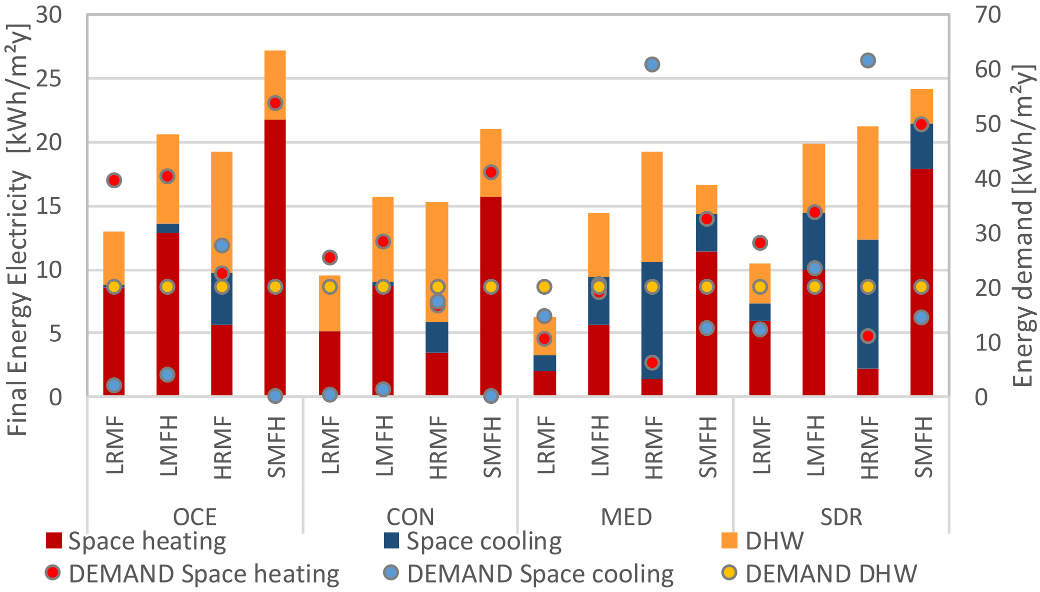


Figure 46 – Final energy consumption and energy demand per building typology and climate

Looking at the solutions in terms of kWh of electricity consumed per energy demand, building typology where more electricity is needed for covering 1 kWh of energy demand is the sMFH, followed by the l-MFH (Figure 47). This result is mainly due to the thermal losses through the pipeline that contribute to increase the produced energy. Despite that, the advantages of these systems lie on the installation costs and the low intrusive works.

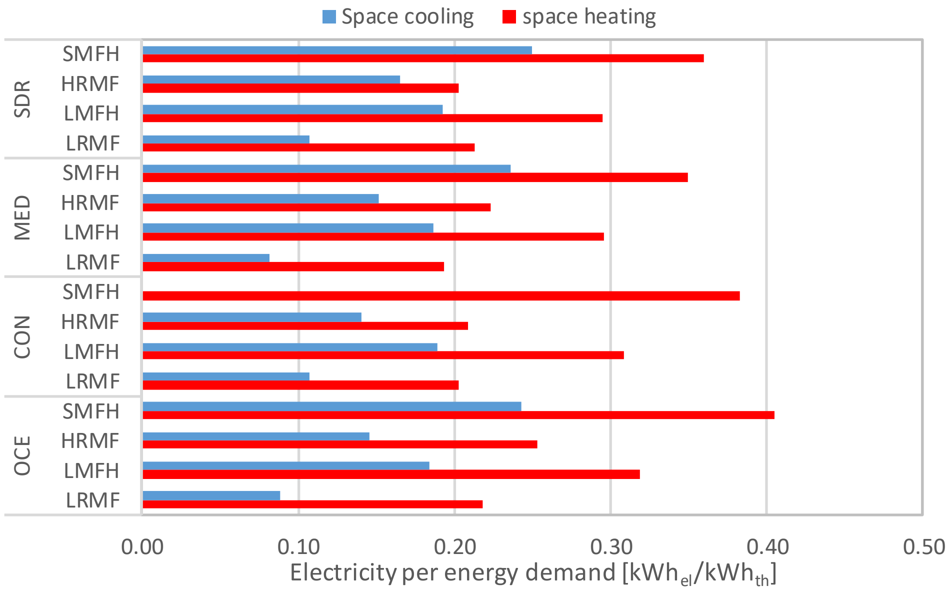


Figure 47 – Ratio between consumed electricity over energy demand for heating (red) and cooling (blue) divided per Climate and building typology

Looking at Primary Energy consumption and savings with respect to the case before intervention, the proposed interventions on the envelope are able to reduce primary energy consumption up to 60%. Only in two cases, high rise building in warm climates, the increase of space cooling is higher than the reduction of space heating. However, the replacement of the existing gas boiler-based heating system and non-efficient split units with centralized or decentralized heat pump systems, can cover the increase of building demand and bring additional primary energy savings. In particular, efficient HVAC systems applied to renovated buildings can reduce primary energy consumption of an existing building in a range of 20-74%. Finally, the use of renewable energies, in the specific solar thermal collectors for centralized systems and PV system, results on a total primary energy reduction of 40-80% depending on the climate and building typology.

Figure 48 shows the Primary Energy consumption of the case before the implementation of the retrofit packages (Reference) and how this decreases thanks to the different interventions. The three darker green columns represent the achieved Primary Energy after the installation of insulation and replacement of the windows (Envelope), the replacement of the HVAC system (Env. + HVAC sys.) and the use of renewable energies (Env. + HVAC sys. + Renew. En.). The dark green column therefore indicates the final Primary Energy of each case after renovation. The proposed solutions are able to cut energy consumption below 50 kWh/m²y for almost all the cases. Exceptions are small MFHs in cold climates as this typology is the one with higher heating demand, keeping same walls transmittance of the other cases.

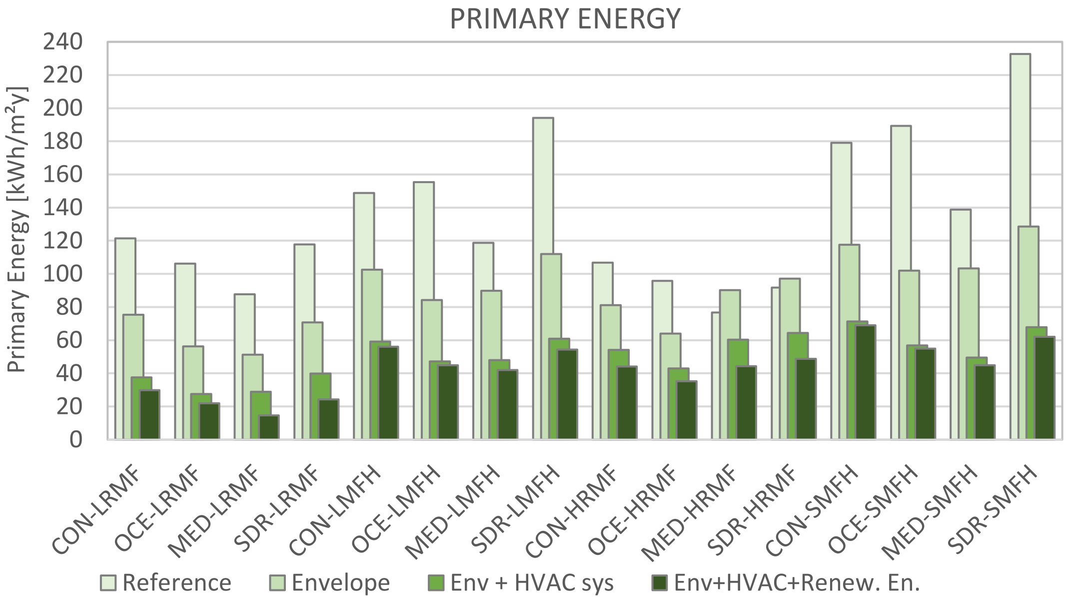


Figure 48 – Primary Energy consumption reduction and final primary energy consumption post intervention for each case thanks to the adoption of the analysed retrofit solutions

5.1.2 Enhancement of HVAC system

Some considerations on the performance of the whole system and of the single devices are reported in the following. This is influenced by the efficiency of the three generation units that for this study, on-the-market products with their performance have been used as reference. More details on the nominal values oh the Elfo pack, ground source heat pump and air-to-water heat pump are reported in sections 3.5.1, 3.6.1 and 3.7.1

The system efficiency increased thanks to the adoption of generation devices able to exploit renewable energy (air, ground) and with higher EER/COP. As a consequence, SPF of the analysed cases ranges between 2.7 and 7 depending on the climate and RS. The highest values are found in RS1 because of the use of a heat pump, together with heat recovery, air recirculation and PV system. Centralized systems (RS3) have a SPF for all the uses in a range of 2.7-2.8 in the coldest climates and 3.1-3.4 in the warmest ones. The decentralized system with ground source heat pumps shows SPFs for the whole system around 3-3.5 throughout the climates.

The lowest system performance is generally verified for DHW production as the working temperature of the machine is where the heat pump COP is lower. However, if DHW is produced with waste heat form cooling production or by electrical resistance exploiting excess PV production, then SPF for DHW during summer season becomes higher. Similarly, higher is the renewable energy contribution, higher will be the SPF. An example is cooling production for the LRMF + RS1 case (Figure 49). The zero value for SPF refers to a case where there is no cooling production, while the yellow arrows indicates high values of SPF for DHW production in summer for the reasons above presented. The green dot indicate the total SPF referred to the whole system.

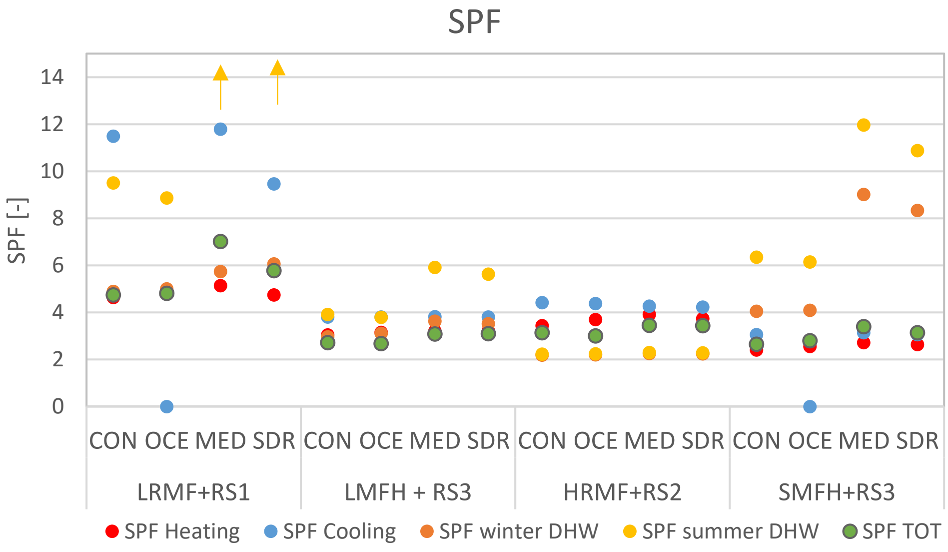


Figure 49 – SPF values for each energy use, building typology and climate

Looking at the seasonal COP and EER (Figure 50), RS1 presents slightly higher values for space heating production than RS3 thanks to the exhaust coil at condenser side that allows to work with higher temperatures than external air. Same consideration is valid for RS2 whose source side is the ground, however SCOP for DHW production results to be lower than the other cases. The reason of this effect lies on the production temperature (52-55°C) that is close to the maximum production temperature. Together with the consumption of the hydraulic pump of the water loop and boreholes, the total SPF for DHW in RS2 results lower than the other cases. SEER results quite performant in RS2 thanks to the favourable working temperatures of the ground, in RS1 SEER is around 3.5, while in the centralized case the seasonal EER value is around 5. This value is obtained by the fact that the selected modulating heat pump shows better performance when working at partial conditions resulting around this value for the whole season.

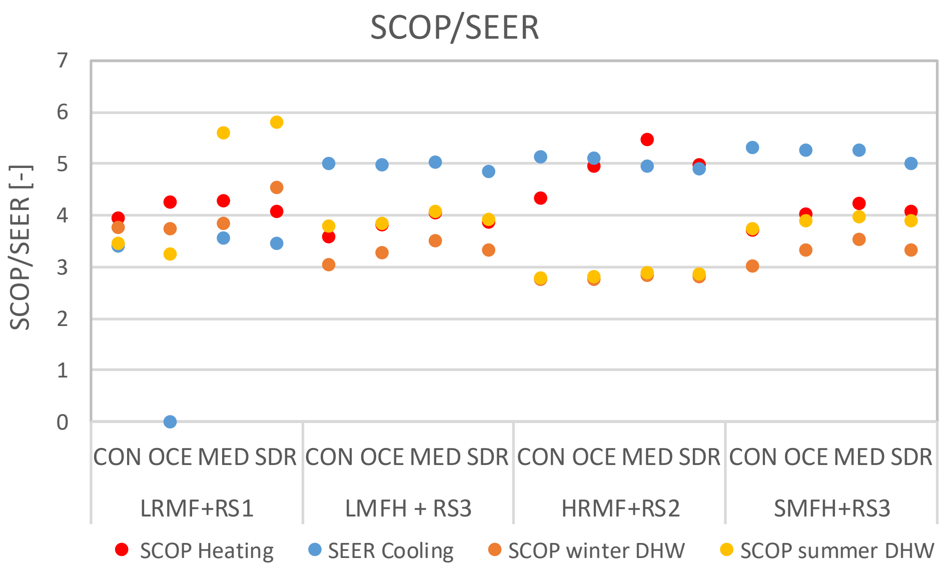


Figure 50 – SCOP and SEER for each energy use, building typology and climate

5.1.3 Use of renewable energy

The impact of renewable energies on the total energy consumption depends on the installed PV capacity, on the simultaneity between PV energy availability and load and on the PV field orientation. Figure 51 shows the total PV production for each case divided in self-consumed energy (red column), energy fed into the grid, that is not exploited overproduction (yellow column) and energy required from the grid (grey column). The quantities are weighted over the heated surface as these results are strictly related to the installed capacity per square meter of lived area. For the LRMF, PV field is 11% of the heated area, in LMFH the share between installed PV and lived area is 4%, in HRMF is 5% and in SMFH is 8%.

The highest values of PV share are observed for the LRMF thanks to the improved control strategy that exploits PV overproduction for DHW uses. However, in the other cases, PV share, that is PV used over the total consumed electricity, ranges between 3% for the northern climates with centralized system and 27% in the southern climates with decentralized systems. To note that the implementation of optimized control strategies for increasing the use of renewable energy could improve this share.

Looking at the red/yellow columns, self-consumed energy with respect to the total PV production is around 25-35% in LRMF case, between 30-40% in LMFH, between 35-50% in HRMF and between 10-20% in SMFH. A low share indicates, in addition to the lack of specific control logics, an oversizing of the PV system with respect to the load to be covered.

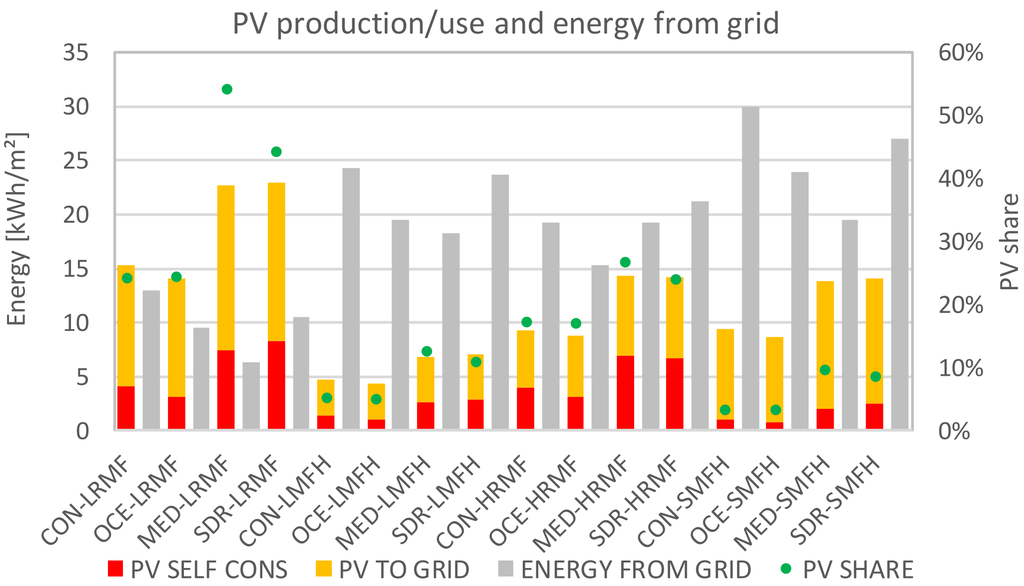


Figure 51 – Summary of energy produced by a renewable source, self-consumed energy and energy taken from the grid for each analysed case.

5.1.4 CO2 emissions reduction

Emissions of CO_2 are calculated based on the conversion factors defined in Table 7.

Looking at Figure 52, CO_2 emission of the cases post intervention (dark green column) ranges between 3 and 14 $kgCO_2/m^2 \cdot y$ depending on the building typology, RS implemented and climate. As already mentioned for high-rise buildings in warmer climates, intervention on the envelope increases the use of energy for space cooling with a consequent higher CO_2 emission. However, in the other cases, envelope insulation and windows replacement can reduce CO_2 emissions up to 50%. The enhancement of the HVAC systems gives an additional

CO2 emissions reduction in the range of 20% to 40% being slightly higher for the decentralized systems.

The use of renewable energy can also give an important contribution achieving a reduction of CO2 emissions up to 20% in the southern climates where solar radiation is higher and cooling demand occurs simultaneously with solar energy availability.

In light of all the contributions that each intervention on existing buildings gives to the final CO2 emissions, the reductions can range from 40% in those cases with the increase of cooling demand due to the higher insulation up to 85% in those cases where decentralized systems are coupled with a PV field and control strategies that improve the use of solar energy are implemented.

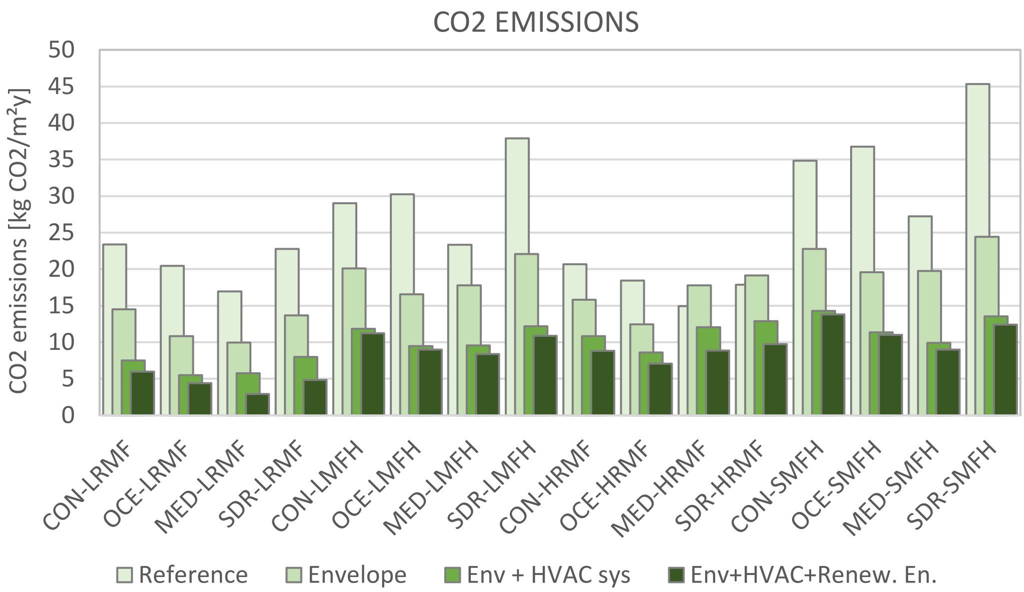


Figure 52 – CO2 emissions of each studied solution before the renovation (whole column), contribution on the reduction by each intervention on the envelope, HVAC system and renewable energy and final CO2 emission after renovation (dark green part)

5.2 Retrofit packages economic performance

The operative costs of each solution are calculated based on the cost of energy referred to the analysed country. As a consequence, the achieved yearly costs savings with respect to the case before renovation depend on the cost of the different energy sources.

In the Southern Dry climate, energy costs refer to Spain and amount to 0.24 €/kWh for electricity and to 0.7 €/kWh for natural gas (see for more details section 2.3.4). The higher cost of electricity per kWh than of gas reduces for the costs the observed savings for energy.

Figure 53 shows yearly costs of the four analysed cases divided by energy use. In the same graph, triangles, dots and squares indicate the building energy demand in order to associate the final costs. Finally, the grey line indicates operative cost of that building before the renovation.

LRMF+RS1 case results the case with lower operative costs and higher costs savings (70%) thanks to the system efficiency and low energy demands for space heating and cooling. Although the HRMF+RS2 almost cancels the costs for space heating, the increase of space cooling and the lower efficiency than the other solutions of the DHW production reduces the savings with respect to the case before intervention of 30%. The centralized system in the two multi-family houses, SMFH and LMFH, have higher operative costs than the other solutions as also the energy demands are higher. However, savings obtained with these cases achieve 65%.

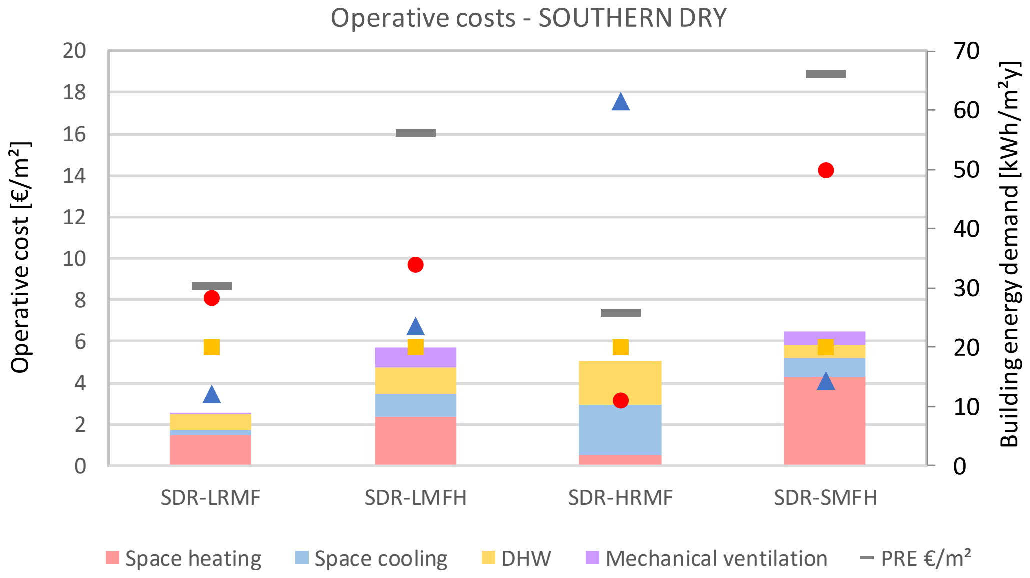


Figure 53 – Operative costs for the four studied cases in the Southern Dry climate; comparison with energy demand and operative costs pre-intervention

In the Continental climate, costs refer to Germany and amount to 0.31 €/kWh for electricity and 0.06 €/kWh for gas, as reported in section 2.3.4. Figure 54 shows yearly costs of the four analysed cases divided by energy use, included energy demands and costs before intervention. Being the cost of electricity 5 times higher than gas, costs savings with respect to the non-renovated case are not significative for some cases.

The LRMF+RS1 shows the lowest operative costs and higher savings (46%) thanks to the system efficiency and typology. The costs for mechanical ventilation are almost fully absorbed by space heating and cooling as ambient conditioning is achieved through an air-system that also guarantees the hygienic air-change rates. The HRMF+RS2 case obtains 22% of savings although this solution does not foresee a mechanical ventilation system. The replacement of an electric boiler for DHW production with a centralized heat pump-based system can show relevant savings also for this case achieving 35-40% in the SMFH and LMFH. Moreover, with the implementation of RS3, renovation works are less intrusive and air quality in the ambient significantly increases.

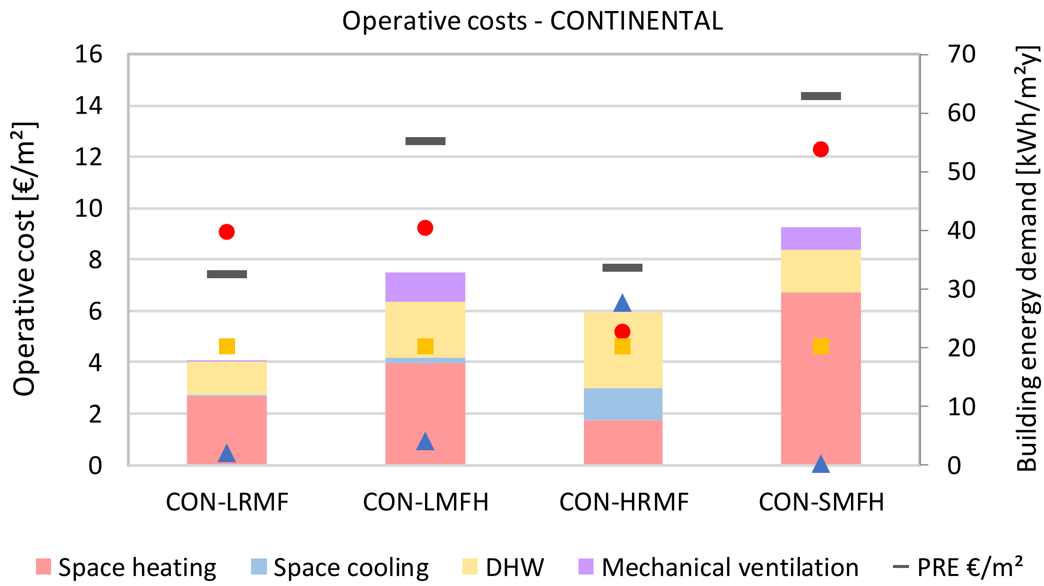


Figure 54 – Operative costs for the four studied cases in the Continental climate; comparison with energy demand and operative costs pre-intervention

In the Oceanic climate, the cost of electricity amounts to 0.21 €/kWh while natural gas is four times less, 0.05 €/kWh. LRMF+RS1 allows to achieve costs savings of 60% with respect to the case before renovation, while HRMF+RS2 a reduction of one third. Thanks to the replacement of the electric boiler for DHW production and the gas boiler for space heating with a centralized heat pump system, LMFH and SMFH + RS3 can reduce operative costs of 55%. Figure 55 shows as these last two cases have higher specific costs than the RS2 although energy demands that are related to the building typology are higher and air quality is increased thanks to the presence of a mechanical ventilation system.

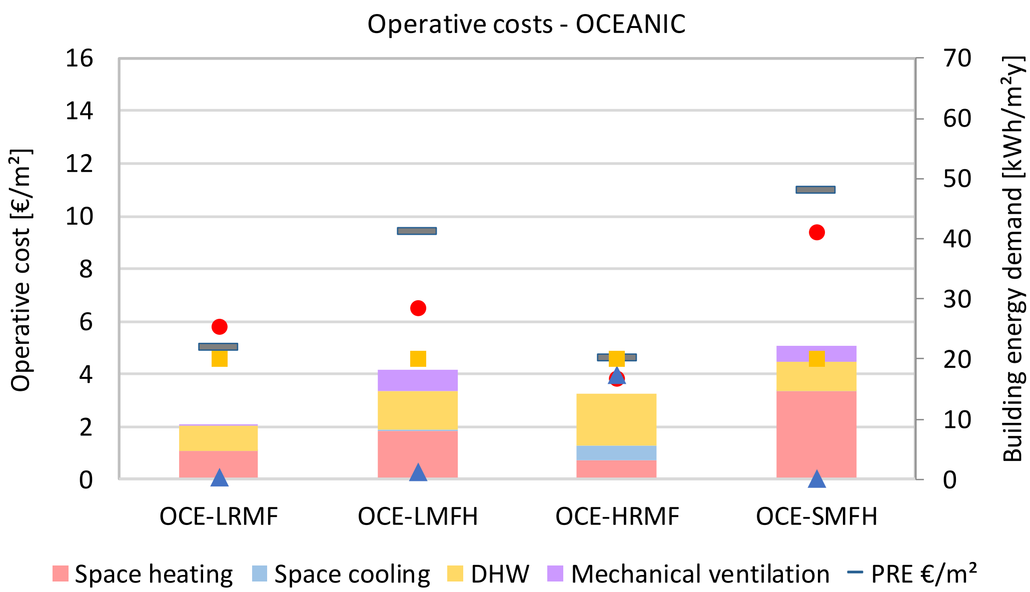


Figure 55 – Operative costs for the four studied cases in the Oceanic climate; comparison with energy demand and operative costs pre-intervention

In the Mediterranean climate, cost of energy for Italy is taken into account and amounts to 0.23 €/kWh for electricity and to 0.08 €/kWh for natural gas. The solution of LRMF+RS1 also in this case results the one with lowest operative costs thanks to the system efficiency, use of renewables and low energy demands of the building. The other three cases show similar operative costs despite the different buildings energy demands. The HRMF+RS2 has very low contribution for space heating, that is compensated by the strong increase of cooling demand and the lower efficiency of the DHW production system. However, savings with regard to the case before intervention amount to 30%. The lower specific space cooling and higher space heating of SMFH than LMFH shows similar operative costs for the centralized systems with mechanical ventilation. Savings with respect to the case before renovation amount to 60% (see Figure 56).

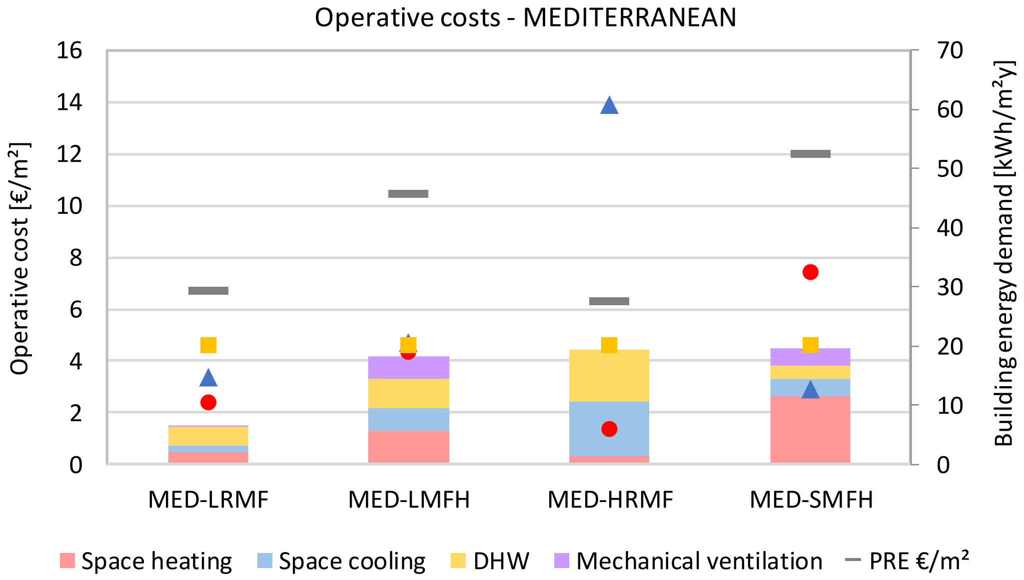


Figure 56 – Operative costs for the four studied cases in the Mediterranean climate; comparison with energy demand and operative costs pre-intervention

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