THE ROLE OF RENEWABLE ENERGY TECHNOLOGIES IN THE ENERGY RENOVATION OF RESIDENTIAL BUILDINGS

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Abstract

The high share of energy consumption of the residential sector and the low renovation rate of existing buildings move through the need of finding solutions that facilitate the retrofit process. Common heating and cooling systems are often not adequate to the building as consequence energy plant operation is not efficient and running costs are high, or renovation works result intrusive and tenants or dwelling owners obstruct their execution.

The here presented study investigates retrofit solutions packages applied to different multi-family house typologies located through Europe. Intervention on the envelope follows the actual national minimum requirements for energy efficiency, efficient heating and cooling systems are recommended for the different building typologies and renewable energies technologies are considered for contributing to the reduction of energy consumption. Energy performance of the retrofit packages, energy savings and running costs are assessed through dynamic simulations for all the studied cases.

Keywords: Renewable energy, building renovation

1. Introduction

The well-known share of energy consumption due to residential buildings and the high percentage of European buildings built before 1990 require the promotion of massive energy renovation actions of the existing building stock. However, this process attempts to spread due to high investment cost, low acceptance of the owners or tenants, non-clear economic, energy and comfort advantages, design effort, intervention works in occupied buildings and definition of the retrofit solution.

Some of these barriers can be overcame by selecting the most appropriate solution for the building typology, avoiding components oversizing and knowing expected energy and economic savings. Commonly, retrofit solutions are constituted by standard layouts and one generation unit that simplifies the installation and management of the whole system, but does not exploit renewable energies neither optimizes the system functioning. Moreover, a standard configuration usually implies components oversizing and consequently high installation and running costs, non-efficient system operation and users discomfort.

Indications on suitable retrofit solutions for specific building typologies, with expected energy savings and operation costs would help and therefore foster the renovation rate. The study presented in the following analyses retrofit packages for four representative building typologies of multi-family houses located in four locations throughout Europe. The retrofit solutions investigate interventions on the envelope following the current national indications of envelope performance, three heating and cooling (H&C) system layouts coupled with renewable energy technologies (solar thermal collectors and photovoltaic PV system). A database of model-based results collects energy performance of the studied cases, calculated through dynamic simulations where the buildings with the proposed renovation packages are modeled and simulated in the four reference locations.

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2. Methodology

2.1. Approach

The approach adopted in this study exploits dynamic energy simulations of buildings with integrated HVAC systems pre (pre-RS) and post (post-RS) renovation to evaluate the impact of refurbishment in terms of energy, environmental and economic indicators.

The developed methodology consists of:

- definition of the reference locations, each representing a typical European climate typology based on Heating Degree Days (HDD) (Custom Degree Day Data, http://www.degreedays.net);
- definition of reference buildings and HVAC system pre intervention (pre-RSs);
- definition of retrofit packages (RPs) to be applied to each pre-RS, including envelope insulation, windows replacement, heating and cooling system efficiency improvement and adoption of renewable energy sources;

2.2. Reference locations

The following presented scenarios are simulated in the typical climatic conditions (typical meteorological year) of four European locations. Each reference climate refers to a country and typical weather conditions of a city are used for the dynamic simulations. Reference locations differ each other of around 500 HDD in order to cover main part of European climates. Table 1 summarizes the four reference climates, with the corresponding country used for building characteristics and national requirements, and the related city for the weather conditions. The fourth column of the table reports the HDD of that city calculated on 18°C basis for the last 3 years (2017-2019). The fifth column shows the average external temperature over the year which characterize the climate.

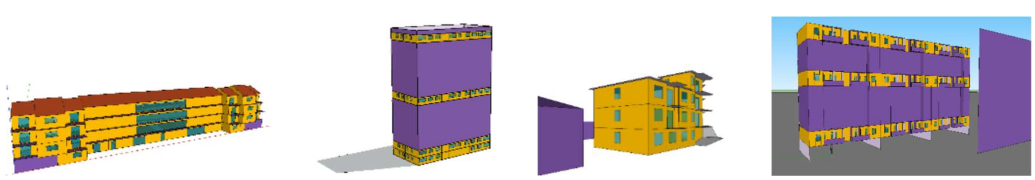
Table 1: Reference climatic conditions and heating degree days

Reference climate	Country	City	Heating Degree Days	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

2.3 Reference buildings and HVAC systems (pre-RSs)

The reference buildings are multi-family houses built between 1980-1990, because 70% of European existing buildings belong to this period (Birchall, 2006) and are still not renovated, which implies a large potential of decarbonization of the residential sector.

In order to consider different buildings shapes, which directly impact on the heating and cooling demands, four building typologies are used with different surface over volume ratio (S/V). The four reference building typologies are: low-rise (LRMF), high-rise (HRMF), small (SMFH) and large (LMFH) multi-family houses. Figure 1 shows a view of the 3D model for each of the considered building typology. Table 2 summarizes the reference buildings geometric characteristics and the HVAC system type in the pre-RS. The four typologies differ for the number of floors, the horizontal development and the total heated area. The shape factors (S/V ratio) ranges from 0.15 for the high-rise building, which despite its height has a compact shape, to 0.45 for the small building.



LRMF HRMF SMFH LMFH

Fig. 1: Reference buildings 3D model view

Table 2: Reference buildings geometric characteristics and HVAC systems (pre-RS)

Building type	Number of floors	Dwell. per floor	Total area	S/V ratio	HVAC –heating (pre-RS)	HVAC –cooling (pre-RS)	HVAC – DHW (pre-RS)
LRMF	4	15	4055	0.34	Decentralized gas boiler (η_{eff} = 0.80)	Split units (EER = 2.5)	Decentralized gas boiler (η_{eff} = 0.80)
HRMF	17	6	7140	0.15	Centralized gas boiler (η_{eff} = 0.80)	Split units (EER = 2.5)	Centralized gas boiler (η_{eff} = 0.80)
SMFH	4	2	712	0.45	Centralized gas boiler (η_{eff} = 0.80)	Split units (EER = 2.5)	Decentralized electric boilers (η_{eff} = 0.85)
LMFH	8	10	7120	0.27	Centralized gas boiler (η_{eff} = 0.80)	Split units (EER = 2.5)	Decentralized electric boilers (η_{eff} = 0.85)

2.4. Retrofit packages

As previously mentioned, each retrofit package is composed by the intervention on the envelope, the HVAC replacement and the adoption of renewable energy technologies.

The intervention on the envelope are aimed at reducing the building demands by improving the envelope performance. The thermal transmittance of the envelope elements in the pre-RS are referred to buildings built between 1980 and 1990. Walls construction changes depending on the location. These values refer to the study conducted during the FP7 project iNSPiRe (Dipasquale et al., 2019). In the post-RS the thermal transmittance are in agreement with the national requirements of the considered location/country for new and renovated buildings. More info in the refence. Since each location is representative of a climate (see next paragraph), Table 3 summarizes the thermal transmittance associated to each climate, both in the pre-RS and in the post-RS.

Table 3: Reference buildings geometric characteristics and HVAC systems

	Pre-RS				Post-RS			
Climate	U_{wall} [W/m^{2}K]	U_{roof} [W/m^{2}K]	U_{ground} [W/m^{2}K]	$U_{windows}$ [W/m^{2}K]	U_{wall} [W/m^{2}K]	U_{roof} [W/m^{2}K]	U_{ground} [W/m^{2}K]	$U_{windows}$ [W/m^{2}K]
Continental	0.65	0.42	0.69	2.92	0.25	0.19	0.23	1.10
Oceanic	0.76	0.59	1.07	4.36	0.18	0.13	0.13	1.40
Mediterranean	1.00	1.24	1.51	4.03	0.29	0.26	0.34	2.00
Southern Dry	1.56	1.33	1.07	3.49	0.41	0.35	0.65	1.80

The replacement of the existing HVAC system is aimed at improving the energy efficiency, limiting/avoiding the use of fossil fuels, and improving the comfort condition of the occupants (including air quality). In all the cases the solutions adopted are mainly based on heat pumps (aerothermal or geothermal). However, very different system layout, distribution schemes, emission devices, and control strategies are adopted depending on the application feasibility and building typology. The HVAC systems configurations are described in Table 4 and are referred to as retrofit solution 1, 2 and 3 (RS1, RS2, RS3). The combination of a building typology with the HVAC system is based on choices that consider the feasibility of the installation (centralized vs decentralized systems) or whose application gives some results that can be extended to similar cases. For further details on the HVAC solutions and the control strategies, please refer to BuildHeat, 2020.

Depending on the building typology and available building external surfaces (roof or external walls oriented to South, East or West), each renovation solution is coupled with a photovoltaic (PV) system only or a solar thermal collectors (STC) system too. PV covers part of the electricity used by heat pumps or auxiliary devices while STC provide a share of Domestic Hot Water (DHW) production. The size of the adopted PV and STC systems is shown in Table 5.

Table 4: Reference buildings geometric characteristics and HVAC systems

Retrofit solution	Main generation	Heating/ cooling emission system	Mechanical ventilation	Solar technologies
RS1	Decentralized air-to-air heat pumps + DHW production	Full-air system	Included in the heating/cooling system with heat recovery	PV
RS2	Decentralized brine to water heat-pumps	Radiators	-	PV
RS3	Centralized air-to-water heat pump	Fan-coils	Decentralized cross flow units with heat recovery	PV+STC

Table 5: Solar technologies installations

Scenario	PV	STC
LRMF+ RS1	55.4 kWp (12% vertical, 88% at 30°)	-
HRMF + RS2	48 kWp (50% vertical, 50% at 30°)	-
SMFH + RS3	10.8 kWp – 10°	37 collectors vertical, south facing
LMFH + RS3	54 kW kWp – 10°	37 collectors vertical, south facing

3. Results

Each combination of reference building plus retrofit solution has been evaluated in each climate for a total number of 16 post-RSs. The impact of each intervention of a retrofit package (envelope insulation, HVAC replacement and adoption of renewable sources) with respect to the case pre intervention pre-RS has been evaluated separately. Considerations on all the cases together and therefore looking at the impact of the climate, the building typology and the adopted solution are also carried out and below reported. For this last analysis, primary energy use (PE) and seasonal performance factor (SPF) were used as key performance indicators.

For each of the 16 cases, in addition to PE reduction, the presence of PV and STC is evaluated in terms of PV share (share of the total electricity consumption covered by the PV) and solar thermal (ST) contribution (share of the DHW thermal demand covered with STC). The economic performance is evaluated in terms of operative cost in a typical year and it also considers the compensation for the surplus PV electricity fed into the grid. All the comparisons and assessment of energy savings, unless otherwise specified, are calculated with respect to the reference case.

In this paper, only part of the results of the presented study is reported. In particular, Mediterranean (MED) and Continental (CON) climates are reported as example of a southern and northern climate, while all the details can be found in BuildHeat 2020. Figures 2 and 3, referred to the MED and the CON climates respectively, show the primary energy consumption in the reference case (first column), PE if intervention on the envelope and HVAC system are implemented (second column) and the total PE consumption when also PV and STC are implemented (third column). PE is divided by energy use: space heating, space cooling, DHW demand and ventilation. On the right axis, it is possible to read the PV self-consumption and STC contribution. Despite the variety of building typologies and renovation solutions and the climates, we can note as the upgrading of envelope thermal characteristics to the current requirements and the use of more efficient HVAC systems can reduce primary energy consumption in a range of 60%-65% with respect to the case pre renovation. Only one exception is HRMF building typology that is characterized by a large number of apartments with only one external surface and located in an intermediate floor. As a consequence, an intervention on the envelope is effective in reducing heating demand, but not for cooling demand. However, the covering of this load with a heat pump allows to register a reduction of PE consumption in order of 25% in the Mediterranean climate where cooling demand is higher and 50% in a northern climate. To additionally increase these savings, renewable energies can give a contribution depending on the installation surface availability and control logics adopted for managing energy production.

In the Mediterranean climate the PV self-consumption on yearly basis amounts to 33% in the LRMF+RS1 scenario, 15% in both HRMF+RS2 and SMFH+RS3 scenarios and 38% in LMFH+RS3 scenario. In the Continental climate the PV self-consumption is 27% in LRMF+RS1 scenario, 12% in HRMF+RS2, 11% in SMFH+RS3 scenario, and 28% in LMFH+RS3 scenario. The increase of PV self-consumption in the warmer climates is due to the more frequent match between the consumption and the PV production, which, in turn, is mainly due to the larger consumption for cooling.

Solar thermal collectors contribute for 28% and 11% of the building total heating production (in the Mediterranean and the Continental climates, respectively) in the SMFH+RS3 scenario and for 5% and 2% in the LMFH+RS3 scenario. The very low ST contribution in the SMFH+RS3 scenario is due to the small south oriented surface where STC is installed corresponding to the surface for 1/5 of the dwellings, whereas the contribution is calculated with respect to the whole building.

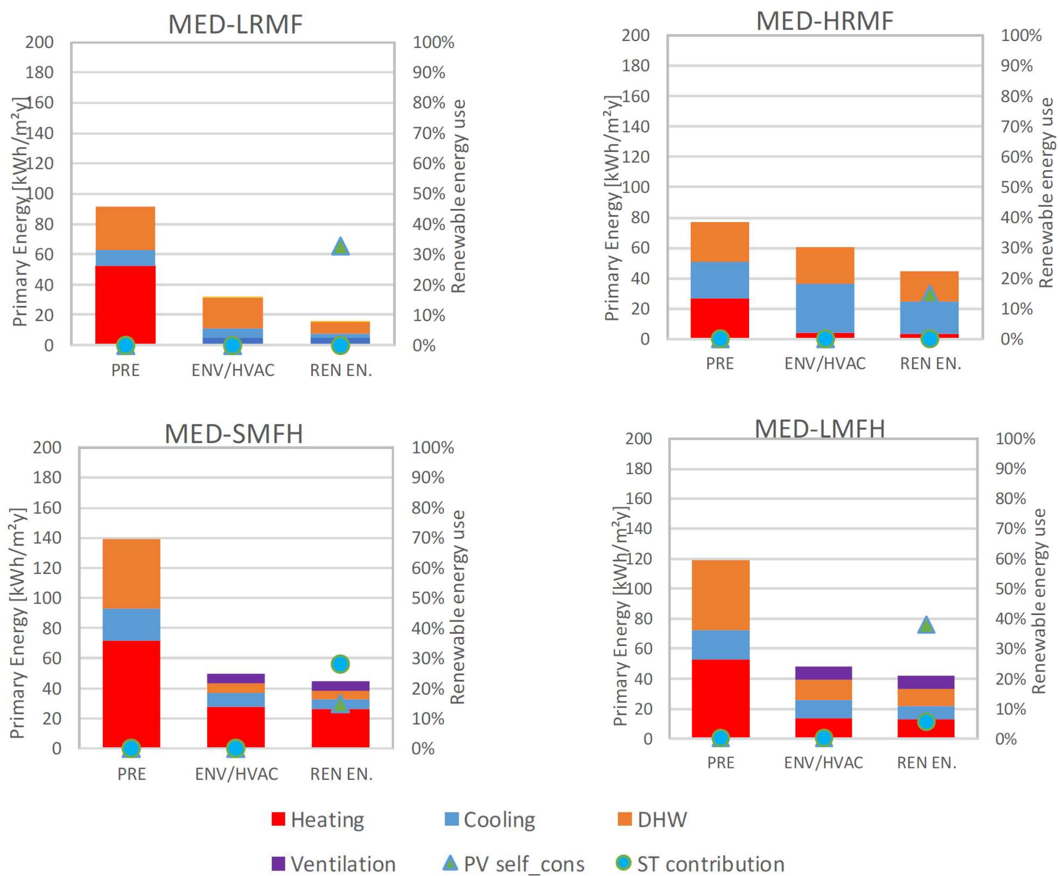


Fig. 2: Primary energy decrease for each intervention and by energy use, PV self-consumption and STC contribution in the Mediterranean climate

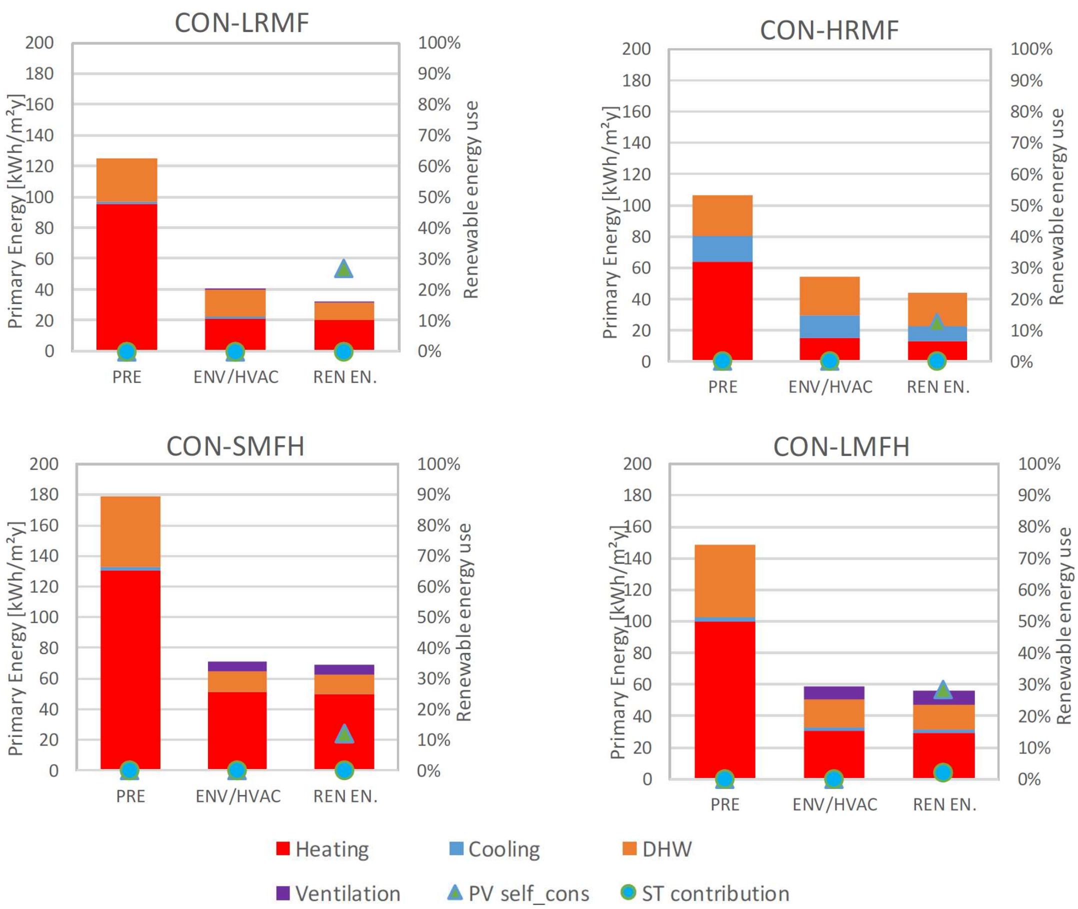


Fig. 3: Primary energy decrease for each intervention and by energy use, PV self-consumption and STC contribution in the Continental climate

Comparing all the results for the four analysed climates, Figure 4 shows PE consumption of the reference case pre-RS in very light green, the PE consumption with intervention on the envelope (light green) and replacement of the HVAC system (green) and with the use of renewable energy too (dark green). Depending on the amount of installed PV or STC, the adopted control strategy, the building typology, HVAC system adopted and climates, PE consumption for post-RS ranges between 18 up to 62 kWh/m²·y with the main cases below 50 kWh/m²·y. Due to the building shape, SMFHs result in higher heating demands and therefore higher PE consumption.

The energy efficiency of the system has been evaluated by considering the Seasonal Performance Factor for each use (space heating, cooling; DHW) and for the whole system. This indicator takes into account all the system losses and auxiliary consumption and it is calculated as the ratio between thermal energy provided to the user for covering its load and electricity consumed for that purpose. The seasonal performance factors (SPF) of the HVAC systems adopted in the renovations range between 2.7 and 7 depending on the climate and RS. Looking at the total SPF of Figure 5, the highest values are found in RS1 because of the use of a decentralized heat pump, together with heat recovery, air recirculation and PV system. Centralized systems (RS3) have a total SPF in a range of 2.7-2.8 in the coldest climates and 3.1-3.4 in the warmest ones as thermal losses have a higher weight on the total SPF. The decentralized system with ground source heat pumps shows SPFs for the whole system around 3-3.5 throughout the climates as temperature at source side is more favourable than external temperatures and slightly differ from one climate to the other. With regard to the single uses (heating, cooling and DHW), the lowest system performance occurs for DHW production in RS2, as the load side working temperature of the machines implies lower COPs. Improvement of SPF for DHW can be achieved by integrating DHW production with a solar thermal system or exploiting waste heat from cooling production (i.e. RS3) or coupling an electrical resistance that exploits excess PV production (i.e. RS1). The zero value for SPF refers to a case where there is no cooling demand.

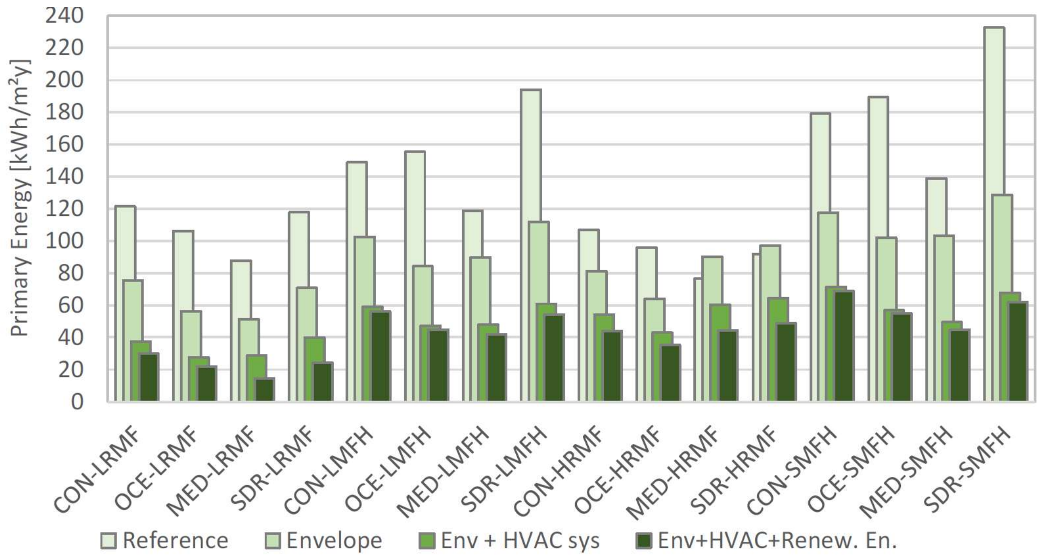


Fig. 4: Primary energy consumption of the pre-RS (Reference) and after the envelope renovation (Envelope), the replacement of the HVAC system (Env. + HVAC sys.) and the use of renewable sources (Env. + HVAC sys. + Renew. En.).

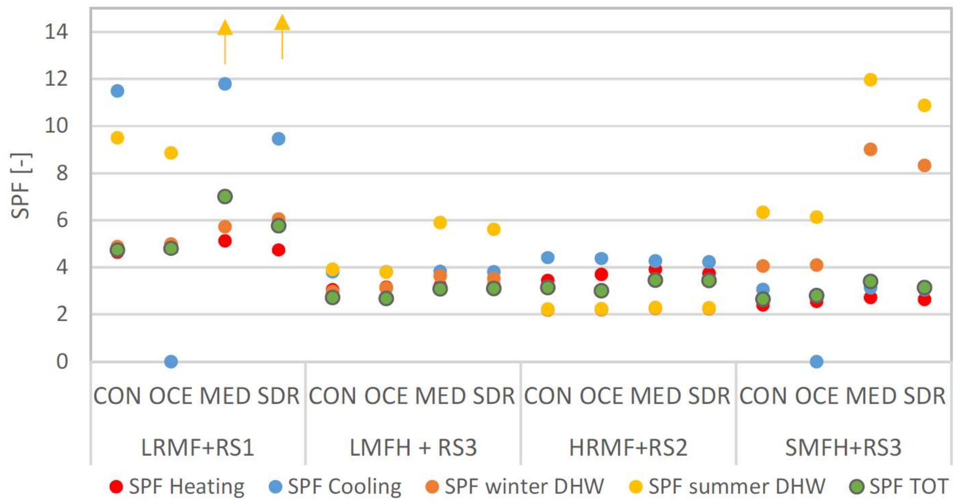


Fig. 5: Seasonal Performance Factors (SPF) for each energy use and for each of the analyzed case

The impact of solar energy on the total energy consumption is very different among the analyzed cases, due to the variety of building loads, solar field typology (PV/ST), sizing, and orientation. Focusing on the PV systems, which are present in all the considered scenarios, Figure 6 shows the total production for each case divided into self-consumed energy (red), and energy fed into the grid (yellow). The energy required from the grid (grey), is also shown. The electric energy is divided by the heated floor area to allow the comparison between different cases.

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.

The highest values of PV share (electric energy from PV over the total consumed electric energy) are observed for the LRMF thanks to the improved control strategy that exploits PV surplus production for DHW uses. This emphasizes the importance of such algorithms for enhancing the use of solar energy. In the other cases, PV share ranges between 3% for the northern climates with centralized system and 27% in the southern climates with decentralized systems. This is in line with results in Bee et al., 2019, where, even with a larger PV area with respect to the floor area, the highest PV share obtained among different European climates without specific control strategy and without electric storage is 40%.

By comparing the LMFH and the SMFH, which are renovated with the same retrofit solution (RS3), a small difference in the PV share can be noticed being higher in LMFHs despite the lower PV installed area over heated area. This can be explained by the lower load distribution over the PV production hours that occurs in a small MFH with respect to a large one, which reduces the match of the total load and PV production. Consequently, the SMFH result the building typology with the highest amount of energy from the grid per m^2 of floor area.

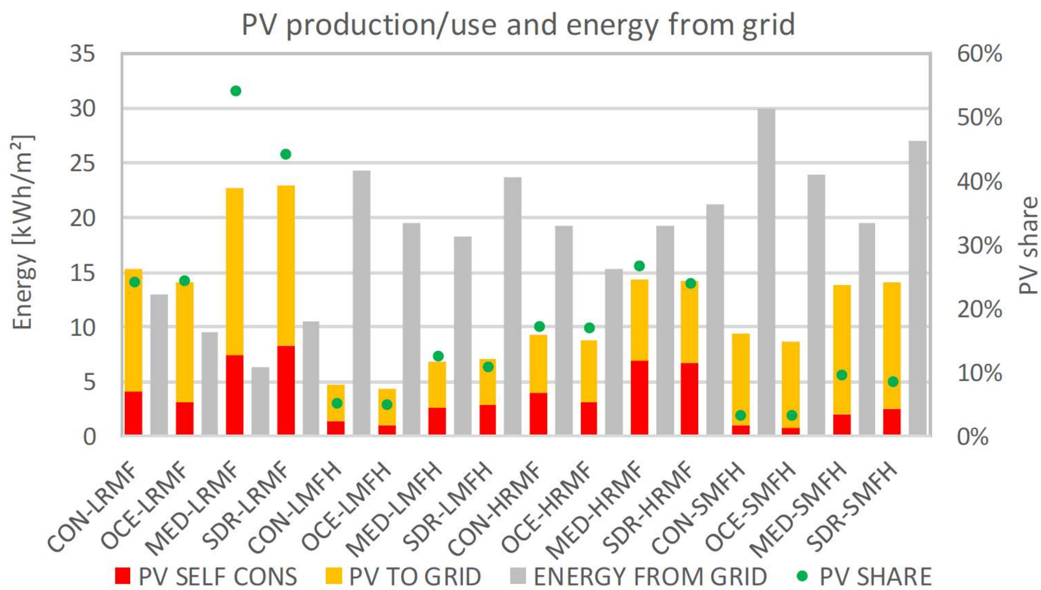


Fig. 6: Comparison of PV share, self-consumed energy, energy fed into the grid and energy taken from the grid, for each of the analyzed case

The annual operating costs of each pre-RS and post-RS are calculated based on the cost of energy (natural gas and electricity) in the four considered countries. Depending on the analyzed case, a specific cost of electricity or gas has been assumed, according to the values given by Eurostat (2019). Table 6 summarizes the adopted values.

In the post-RSs, there is a surplus of electric energy which is not directly used (yellow bar in Figure 6) but is fed into the grid. Each country applies (or could not) a different policy for selling energy fed into the grid with different prices. In this regard, the European scenario is quite complex and not uniform (Banja et al., 2017; Fruhmann and Tuerk, 2014). For this reason, we have analysed three scenarios that consider a different compensation of the surplus energy. First scenario assumes that surplus energy is bought at same cost as energy from the grid; in the second scenario, surplus energy is paid half of the energy from grid while in the third scenario surplus energy is bought at zero cost, so considering as it came from PV production.

In the following, total operating costs (C_{tot}) in the post-RS are calculated in these three different conditions, which involve different economical compensations, on an annual basis, for the surplus energy fed into the grid ($E_{to\ grid}$):

a. Scenario 1: no support scheme is applied: $C_{tot} = E_{fromgrid} \cdot P_p$

b. Scenario 2: compensation at 50% of the purchase price (P_p): $C_{tot} = E_{from\ grid} \cdot P_p - E_{to\ grid} \cdot 0.5\ P_p$

c. Scenario 3: compensation at 100% of the purchase price (P_p): $C_{tot} = E_{from\ grid} \cdot P_p - E_{to\ grid} \cdot P_p$

Where $E_{fromgrid}$ is quantity of electricity taken from grid; the P_p is the purchase price that is the unitary price of energy in the reference countries (Table 6); E_{togrid} is surplus energy fed into the grid and re-used by the building.

Table 6: Unitary prices of energy in the reference countries

		Germany	United Kingdom	Italy	Spain
Electricity	€/kWh	0.3088	0.2122	0.2301	0.2403
Gas	€/kWh	0.0632	0.0493	0.0769	0.0736

The results are shown in Figure 7 in terms of operating cost per m^2 of building floor area. The grey column represents operating costs of the pre-RS, the green column refers to the operating costs post-RS without any compensation policy (condition a), in the blue column the operating costs are calculated with the simplified net-metering scheme with conditions b and the orange with conditions c. Looking at all the analysed cases and considering the first scenario (green column), annual cost reduction from pre-RS to post-RS ranges from 22% to 78% thanks to the improvement of the building envelope, of the HVAC system efficiency and of the renewable energy use. By applying a scenario b, the further saving ranges from 7% in the Continental climate with the LMFH to the 100% in the Mediterranean climate with the LRMF building (complete compensation of the purchased electricity) as this solution already foresaw very low electric consumption. By applying scenario c, additional costs savings can be achieved, from 15-20% in the LMFH up to 40% in HRMF and 60% in SMFH in the Mediterranean climate. Under condition c, annual costs for heating and cooling uses in multi-family houses lies below 5 €/kWh for almost all the cases, with exception of two cases in the Continental climate where building loads are higher and PV production lower and unitary cost of energy is quite high.

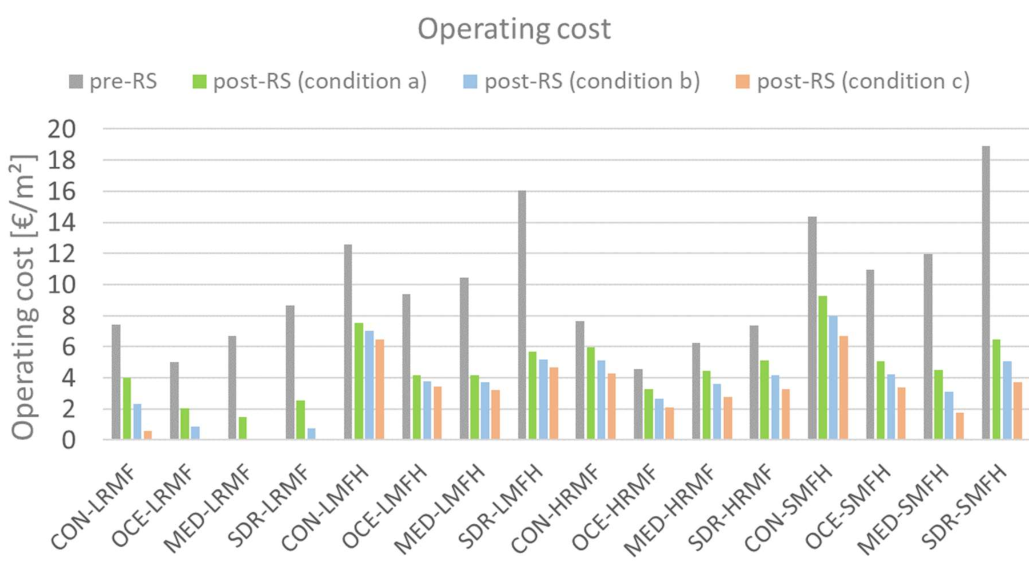


Fig. 7: Operating costs in the pre-RS and in the post-RS with different compensation schemes for the electricity.

4. Conclusions

In this study, a set of renovation measures for multi-family houses are analysed, considering a variety of building typologies, retrofit solutions, and climates. The results from the dynamic simulations prove that the adopted interventions can lead to a significant primary energy reduction in all the climates, while improving the comfort condition for the occupants. The impact of the solar energy technologies on the primary energy reduction is small if compared to the contribution of the envelope renovation and the HVAC replacement, but contributes on the PE consumption of the different uses in the order of 5% for DHW up to 20-30% for space cooling and 40% where PV use is optimized with specific control strategies. As a consequence, renewable energy contribution becomes key especially in those cases where cooling demand is not negligible.

Better exploitation of renewable energy use can be achieved by implementing control strategies that maximize the match between energy production and energy consumption and reduce the surplus of energy fed into the grid. This aspect is also highlighted by an analysis on the operative costs that shows as a support scheme based on the net-metering can lead to the complete compensation of the cost for the electricity purchase where total electricity consumption is close to the overall PV production or to additional savings on the operative costs of an average of 30-40% depending on the electricity use and PV production. Despite the economic analysis conducted does not focus on the renovation investment cost and payback time, a significant reduction of the annual operating cost in all the scenarios shows the profitability of the intervention.

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