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Model-Based Design of a Solar Driven Hybrid System for Space Heating and DHW Preparation of a Multifamily House

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Abstract

Following the most recent European Directives on Energy Performance of Buildings and Energy Efficiency, new solutions for DHW production, space heating and cooling have to be developed and applied to reduce the primary energy consumption of residential buildings.
Due to the complexity of installation and control, H&C hybrid systems exploiting a mix of conventional fuels and RES are not yet widespread although they can bring important savings to the yearly building energy consumptions.
This work summarizes the parametric analysis used as part of the design process of a hybrid system for the retrofit of a multifamily house located in Madrid, and shows how heating, cooling and DHW demands of multifamily houses can be covered by a heat pump plus solar systems, integrating a high share of RES. The design of the system has taken into account energy savings, economics and architectural aspects.

Keywords: Solar DHW, Buildings retrofit, Hybrid systems, Solar + heat pump systems, Energy savings

1. Introduction

Residential buildings in Europe cover an area of approximately 17.6 billion m², and out of this, 15.1 billion m² is estimated to be heated [1]. Moreover, the residential sector contributes largely to the energy consumption with around 40% of the EU energy use [2]. The age distribution of the residential building stock varies from country to country,

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but the age of houses is broadly similar across Europe with a growth rate peak between 1950s and 1970s. The DHW demand in Europe is estimated to be about 21 kWh/m²y, while the heating demand averages around 150 kWh/m²y despite the large variability due to construction typology and age of construction [1].

In light of this, several directives, in particular the 2010 Energy Performance of Buildings Directive [3] and the 2012 Energy Efficiency Directive [4] pursue the reduction of the energy consumption of buildings, promote the refurbishment of existing buildings and the use of RES in H&C systems.

Aim of this work is to show how large energy savings can be achieved through the retrofit of the envelope and H&C system, having an existing building with high-energy demands and decentralized H&C systems as a starting point. The study takes as a reference a multifamily house located in Madrid and actually being retrofitted with a solar thermal collectors and air to water heat pump system. In particular, we summarize the parametric analysis used as part of the design process of a hybrid systems. Starting from the actual status, savings in terms of useful and primary energy are assessed for the renovated building for a number of combinations.

We conclude the analysis with the comparison of the study with the actual installation selected for the retrofit of the building.

Nomenclature

AWHP	Air to Water Heat Pump
DHW	Domestic Hot Water
ED	Energy Demand
EL	Energy Level
H&C	Heating and Cooling
PE	Primary Energy
PV	Photovoltaic
RENF	Renewable Energy Fraction
RES	Renewable Energy Source
ST	Solar thermal

Subscripts

C	Cooling
H	Heating
DHW	Domestic Hot Water

2. Description of studied combinations

The reference building is a multifamily house situated in Madrid, with 10 dwellings distributed on 5 storeys (see Fig.1). The building has been built in the 70s, when neither insulation nor centralized H&C systems have been foreseen during the initial planning phase. For this reason, during the years, each owner has installed its own decentralized gas boiler and electric heaters. An energy model of the building has been created for the case before renovation, and calibrated based on auditing data and utility bills. Only a few of the dwellings are setup with a split unit for summer air conditioning.

The heating and cooling reference demands, of the existing building has been calculated to be 91 kWh/m²y for the heating and 38 kWh/m²y for the cooling - assuming set temperatures of 20°C and 25°C in winter and summer respectively. While calculated heating demand is well in line with the monitored data, the cooling demand is slightly representative since only a few of the dwellings are partially cooled in summer.

2.1. Envelope renovation

The renovation of the building envelope consists in setting up an insulation layer on the external walls and roof. New double glazed windows are installed on the outside of the existing ones.

Windows and insulating characteristics are reported in Table 1.

A mechanical ventilation system is also foreseen with respect to the highest energy standard.

Notice that two different building Energy Levels (EL), based on heating demand, have been individuated according to different insulation thickness for the present study. The best solution has been actually selected for the retrofit of the building.

The so defined buildings allow a reduction of the building heating demands of around 40% for the 55 EL and 83% for the 15 EL. The cooling demand, instead, increases of around 10% for both cases, due to the higher building thermal mass that tends to maintain the solar gains inside the building also during the summer. This is to be carefully considered when planning the retrofit mostly when cooling is not prior installed, since this can significantly affect the final savings' calculation and owners' energy bill.

Fig 1. Picture of the multifamily house located in Madrid

2.2. Generation and distribution systems configurations

The most common energy plant for space heating and DHW production is made of a centralized gas boiler (BLR) which feeds the radiators placed in each dwelling (see Fig.2 left). The eventual cooling demand is therefore covered by split units installed in each flats. This system is a simple and well known technology. The main drawback is the inability to exploit renewable energy sources, therefore, the impossibility to reach the minimum requirements requested from the latest European Directives [4].

The system considered here is made of a condensing boiler of 25 kW used for space heating and DHW preparation. The space cooling is guaranteed by split units. A 450 l thermal storage is used for the DHW preparation. For the distribution, radiators are installed in the flat. The radiators supply temperature is 45°C in order to be compared to low temperature solutions.

To integrate and increase the penetration of renewable energies in buildings, other technologies such as heat pump generation systems that exploit air, water or ground energy sources must be used. An Air to Water Heat Pump (AWHP) is integrated in the renovated system of the presented case. In the study, the heat pump has been used for heating and cooling as well as for the DHW preparation. A thermal storage is used for the DHW, while a small buffer stores the cooled or warmed water for the distribution in addition to be used for the heat pump de-icing. A sketch of the H&C system is shown in Fig.2 (right). The distribution system that better exploits the heat pump potential is the coupling with a low temperature solution, in this case radiant ceilings. This system can be easily installed, the visual impact is limited, and therefore it suits for building refurbishment solutions.

A 20 kW AWHP covers the demands of H&C and DHW. The distribution is done by radiant ceilings fed by a supply temperature of 35°C. A 450 l thermal storage is used for the DHW distribution, while a smaller 80 l buffer stores energy for the distribution and de-icing.

Table 1. External surface transmittance for existing and two renovation solutions.

Typology	Existing case	Renovated case- 15 EL	Renovated case- 55 EL
Window	Single pane (U=5.7 W/m^{2}K)	Double pane (U=1.79 W/m^{2}K)	Double pane (U=1.79 W/m^{2}K)
External wall	No insulation (U=1.53 W/m^{2}K)	6 cm of insulation (U=0.49 W/m^{2}K)	2 cm of insulation (U=0.99 W/m^{2}K)
External Roof	No insulation (U=2.88 W/m^{2}K)	6 cm of insulation (U=0.48 W/m^{2}K)	2 cm of insulation (U=0.94 W/m^{2}K)
External Floor	No insulation (U=2.37W/m^{2}K)	No insulation (U=2.37 W/m^{2}K)	No insulation (U=2.37 W/m^{2}K)

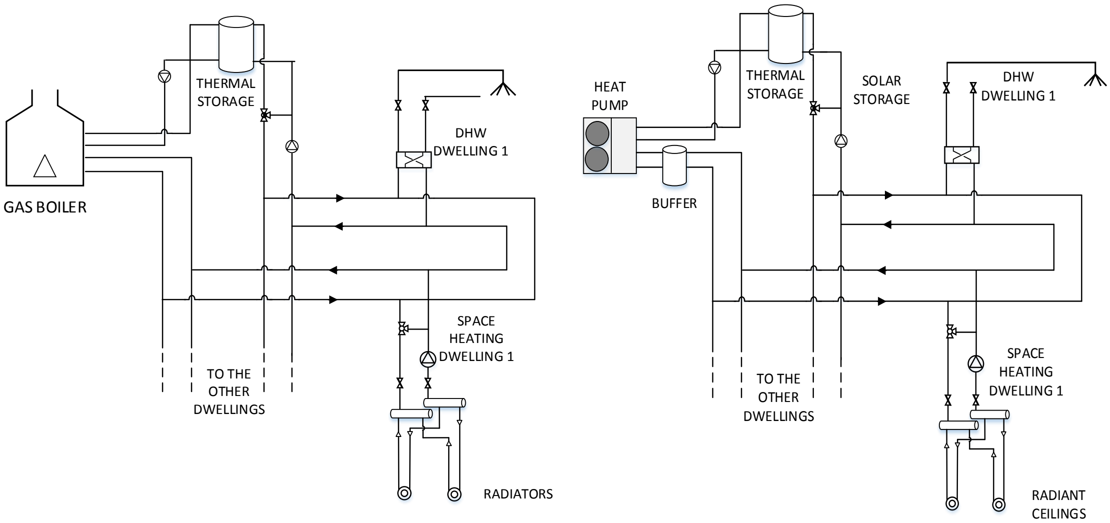

Fig. 2. Layout of the centralized gas boiler (left) and air to water heat pump (right) configurations.

2.3. Solar technologies

The ratio of renewable sources in H&C systems can be increased thanks to the use of solar thermal (STC) or photovoltaic panels (PV).

The solar thermal field considered in this analysis is built with flat plate collectors with a total area of 27 m² positioned on the roof parapet with a tilt angle of 90° oriented south. The Thermal Energy Storage (TES) has been sized assuming a ratio of 50 l/m² of collectors' area [8]. This value is positioned at the lower edge allowed due to volume availability limits for the technical room.

The contribution of PV panels has been assessed with a slope of 30°, south oriented and installed on the flat roof. The PV field considered is limited to 24 m² due to space availability reasons, corresponding to around 3 kW of peak power.

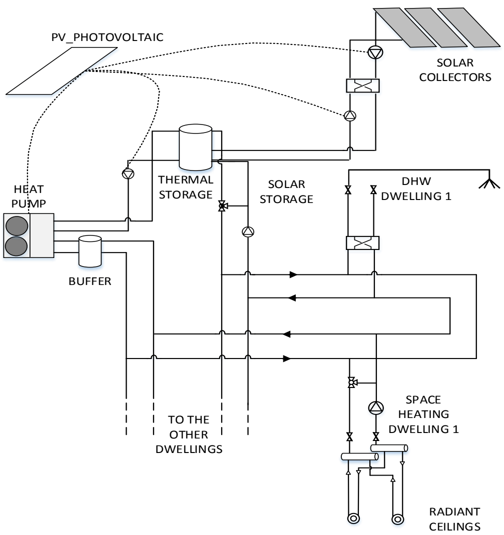

Fig. 3. Layout of the solution with AWHP with solar thermal collectors and PV.

2.4. Integration of the different solutions

The solutions analyzed integrate the AWHP with solar thermal or/and photovoltaic panels (Fig. 3). Specifically, an AWHP provides heat and cold to cover the space conditioning and DHW demand. The solar thermal field harvests solar energy mainly used for the DHW preparation during the whole year and, in smaller fractions, for the space heating. The PV system covers primarily the electricity consumption of the H&C system, the building uses secondarily, and what remains is fed into the grid.

3. Methodology

The configurations presented above have been simulated in TRNSYS. Performance figures have been used to compare the different solutions and assess the potential energy savings and system performance. Simulations results have been used for supporting the design process and assist on the system sizing.

3.1. Configurations assessed

Starting from a commonly used system for space conditioning and DHW preparation made of gas boiler + radiators and split units, the analysis went through the use of an AWHP and the coupling of this with solar technologies as thermal panels and photovoltaic. Table 2 summarizes the combinations analyzed and the nomenclature used.

Solution 1 represents the reference case with gas boiler, radiators as distribution system and split units. Solution 2 is set up with an AWHP and radiant ceilings delivering both heating and cooling. Solution 3 and 4 integrate solar thermal collectors and PV panels in Solution 2, respectively. Solution 5 considers that both ST and PV fields are used.

Table 2. List of the simulated cases and related nomenclature.

Configuration	EL 15	EL 55
Solution 1: BLR + RAD	C1_15	C1_55
Solution 2: AWHP + CEI	C2_15	C2_55
Solution 3: AWHP + CEI + STC	C3_15	C3_55
Solution 4: AWHP + CEI + PV	C4_15	C4_55
Solution 5: AWHP + CEI + STC + PV	C5_15	C5_55

Forsake of completeness, type 927 was used for the heat pump simulation. The numerical model reads a lookup table for the device performance, built from the manufacturer data. The thermal storage is the type 340, while the radiant ceilings are modeled with type 1362. ST collectors are modelled with type 832 made by SPF [7], while PV panels have been assessed using type 194.

3.2. Performance figures

The performance of the H&C system is assessed as follows:

- Energy Demand (ED) represents the specific energy provided to the building by the distribution system to maintain comfort conditions in terms of temperatures and relative humidity. The ED is referred to the floor area of the building (kWh/m^{2}y) and it is evaluated for heating, cooling and DHW loads.
- Primary Energy (PE) represents the form of the equivalent source which every energy carrier can be attributed. To evaluate the Primary Energy, non-renewable Primary Energy factors of 2.88 and 1.19 are used for electricity

and gas respectively [9], [10]. Solar Fraction (SF) represents the fraction of the ED covered by solar thermal energy. It is calculated for the heating and DHW demand.

- Renewable Energy Fraction (RENF) represents the fraction of the ED that is covered by RES, e.g. solar energy from thermal collectors (ST) and photovoltaic (PV) or air from the heat pump.

Economic considerations are based on annualized costs defined as follows:

- Investment Costs (IC) are calculated according to the Net Present Value method over an investment horizon of 30 years, taking into account i) initial investment costs I_0; ii) replacement costs C_r; iii) operation linked payments (maintenance costs, insurance, taxes) C_m; iv) consumption linked payments (final energy costs) C_{fe}.

4. Results and comments

The results of the simulations are referred to the two refurbishment energy levels. Looking at Table 3and Table 4 the simulated heating demands are slightly different compared to the ideal goal. This mismatch is due to the deadband on the set temperature (0.5°C) and to the effect of system control strategy. Moreover, the calculation of the demands is also influenced by the ratio between radiative and convective fraction of the distribution system. While the ideal energy demand calculation as well as the distribution with the radiators considers 70% emitted energy through convection, the radiant panels convective effect amounts to only 30%. In this contest, it is evident how different distribution systems cause different EDs for heating and cooling. This difference can be justified looking at the operative temperature (higher in case of radiant ceilings).

Table 3. Performance figures for the building with EL 15.

	ED_H	ED_C	ED_DHW	SF_H	SF_DHW	RENF_H	RENF_C	RENF_DHW	RENF_TOT
		[kWh/m²y]		[%]	[%]	[%]	[%]	[%]	[%]
$C1_{15}$	13.8	41	22	0%	0%	0%	0%	0%	0%
$C2_{15}$	15.5	42	22	0%	0%	67%	0%	61%	39%
$C3_{15}$	15.5	42	22	13%	75%	71%	0%	88%	49%
$C4_{15}$	15.5	42	22	0%	0%	72%	18%	61%	51%
$C5_{15}$	15.5	42	23	13%	75%	75%	18%	88%	59%

Table 4. Performance figures for the building with EL 55.

	ED_H	ED_C	ED_DHW	SF_H	SF_DHW	RENF_H	RENF_C	RENF_DHW	RENF_TOT
		[kWh/m²y]		[%]	[%]	[%]	[%]	[%]	[%]
$C1_{55}$	53.6	39	22	0%	0%	0%	0%	0%	0%
$C2_{55}$	57.7	44	22	0%	0%	61%	0%	62%	46%
$C3_{55}$	57.7	44	22	8%	69%	64%	0%	85%	53%
$C4_{55}$	57.7	44	22	0%	0%	65%	15%	62%	55%
$C5_{55}$	57.7	44	23	8%	69%	67%	15%	85%	59%

Looking at the results for the building with EL 15 (Fig. 4a) and considering C1 as the base case, the only use of AWHP allows an increase on RENF of almost 40%. This improvement is due to the exploitation of air in heating mode and DHW preparation.

Both solar technologies (C3 and C4) improve the RENF of another 10%, ST having a higher effect on the DHW production (C3) and PV (C4) on the cooling production.

The integration of the 3 technologies (case C5) increases the renewable fraction to almost the 60% compared to the base case. Similar considerations can be done for the building with 55 EL (see Fig. 4b right and Table 5).

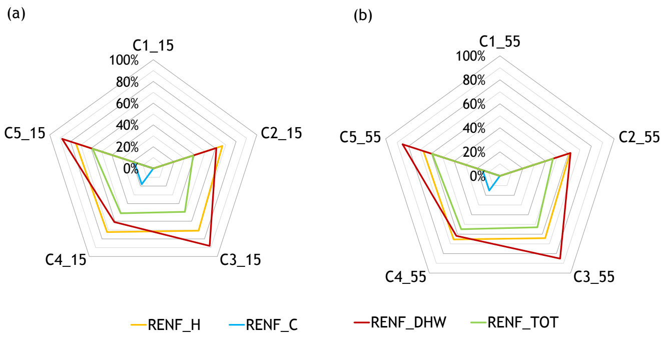

Fig. 4. RENF for all cases: (a) Building EL 15, (b) Building EL 55.

According to the increase of the RENF from C1 to C5 a reduction of PE consumption is obtained. As already observed with respect to the RENF, the use of solar thermal collectors acts more on the PE consumption for DHW production, while PV systems contribute more on PE savings for cooling.

The PE savings calculated with respect to the base case range around 30% if the AWHP is coupled with STC or PV plants. The maximum PE savings are reached in case C5 with a total 54% (Fig. 5a).

With respect to the PV installation, it can be noticed in Fig. 6, that the large majority of the produced electricity is self-consumed within the building, rendering the need of storing electricity or feeding it into the grid irrelevant.

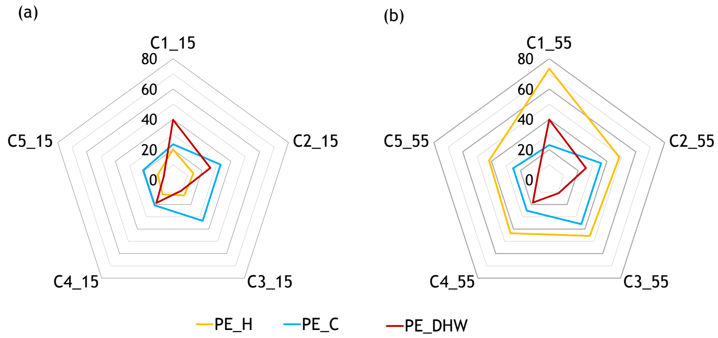

Fig. 5. PE for all the cases: (a) 15 kWh/m^{2}y cases, (b) 55 kWh/m^{2}y.

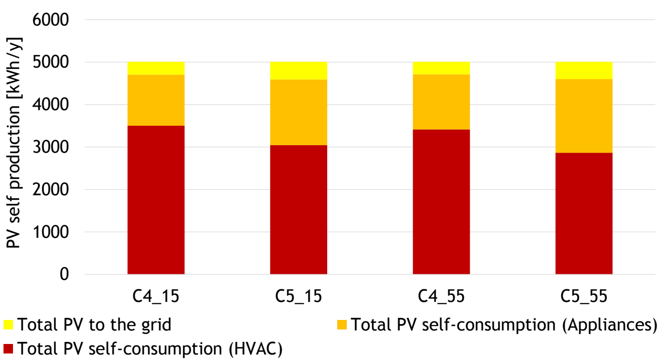

Fig. 6. PV self production for 15 kWh/m2y cases (column 1 and 2) and 55 kWh/m2y (column 3 and 4).

Finally some considerations on the economic aspects. Fig. 7 reports the annualized costs (€/m^{2}y) of insulating the envelope, windows, generation and distribution system as well as final energy and building maintenance. Windows play a major role on the total costs. Since the insulation thickness is limited the installation cost plays a relevant role and no significant difference is noticed between EL15 and EL55.

Regarding the generation system, the EL15 has higher costs because of the mechanical ventilation system. The distribution system costs are slightly higher in the EL55 because of the higher heating load and, consequently, the bigger radiant ceiling surface installed.

The final energy costs have also an important impact on the annualized overall costs, despite the low energy levels considered.

The difference between the two ELs of the overall annualized cost is in the range of 10% for the last three cases. This means that a higher investment costs in the refurbishment is then lessened by lower final energy costs. Vice versa, buildings with higher energy demands, and consequently final energy costs, corresponds to lower refurbishment investment costs.

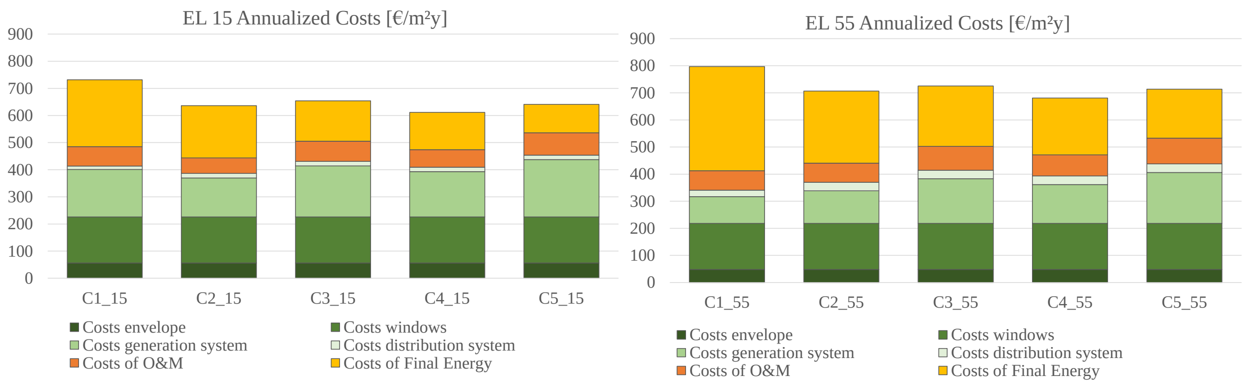

Fig. 7. Annualized costs of envelope renovation, HVAC and DHW systems, maintenance and finale energy for the 15 EL (a) and 55 EL (b)

5. Conclusions

Following the latest European Directives, a reduction of the building energy consumption is possible if the refurbishment of the existing building stock acts on the envelope as well as on the H&C and DHW production systems. A promising solution for the retrofit of the H&C system lies in the hybrid systems.

This paper addressed the energy assessment through numerical simulations of a hybrid system installed in a multifamily house located in Madrid.

Simulations results show how a façade mounted solar thermal field can cover up to 75% of the yearly DHW demand. The remaining is provided by an AWHP. If solar energy exceeds the DHW demand in winter, ST can provide a small contribution to space heating, in the range of 10%.

ST and PV systems contribute equally to the reduction of PE, while also investment costs are only marginally varying: costs for the investment are lower than 300 €/m^{2}y (annualized investment costs 400 €/m^{2}y).

If more than 50% RES exploitation is needed with respect to H&C system – which is already a requirement in some European national regulations – the two solar technologies are to be used in a synergic manner. The integrated use of ST and PV produces a marginal burden on the annualized investment costs too.

Despite the technical considerations, the choice of one or the other technology is in most cases related to the surface availability, architectural integration and possible incentives. Having in mind the case in Madrid, not all the solutions could be implemented. Since integration of PV into the grid is subject to taxation, while compensation measures (like feed-in tariff) are not available to date, it was decided to skip the installation of the PV field.

Architectural integration issues intervened with respect to the solar thermal field. To preserve the aesthetic of the façade, the architect decided that only 18m^2 of collectors could be installed, reducing substantially the SF associated with the H&C system.

The PE energy reduction with respect to a simple gas boiler system is still significant and a total PE level of less than 50 kWh/m^{2}y can be reached. However, non-technological questions should be considered as main drivers already in the preliminary stages of the H&C system design. Additionally, all the parties implicated in the planning (energy consultant, architect, owners, installers) have to be involved in the early stages of the process.

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Appendix A. Primary Energy consumption results

Table 5. PE consumption (kWh/m²y) and savings (%) for the building with EL 15.and EL55.

PE_H		PE_C		PE_DHW		PE_TOT		ΔPE	
$C1_{15}$	$C1_{55}$	$C1_{15}$	$C1_{55}$	$C1_{15}$	$C1_{55}$	$C1_{15}$	$C1_{55}$	$C1_{15}$	$C1_{55}$
20	73	24	23	40	30	83	136	-	-
14	49	33	36	26	25	73	110	-13%	-19%
13	46	33	36	9	11	55	92	-34%	-32%
12	43	21	25	19	18	51	87	-39%	-36%
11	42	21	25	7	8	38	75	-54%	-45%