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Comparison of different heating generator systems to reduce energy consumption in social housing in a Mediterranean climate.

Comparison of different heating generator systems to reduce energy consumption in social housing in a Mediterranean climate.

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Abstract. This study analyses the energy consumption of a social housing built in the 80's. This building typology is deteriorating over time with increased energy consumption for air conditioning and indoor comfort that is well below the standard. This typology is also widely diffused in the city's building stock, especially in its suburbs. Thus, the energy efficiency of public social housing represents a major concern for the Italian national scene, and its improvement represents an effort of critical importance. However, public funding is significantly reduced compared to the past and. In addition, it is often difficult to act on passive systems, such as installing thermal insulation, or replacing terminal units inside apartments. In these cases, as an energy retrofit, it may be appropriate to evaluate the possibility of preserving as much of the existing distribution and supply system as possible, while modifying the thermal energy generation system. In general, where the boiler is not obsolescent, the idea is to propose a hybrid generation system with the inclusion of a heat pump (HHP), which could be implemented with renewable energy equipment, properly installed in the building. The main goal of the present work was to evaluate through dynamic analysis different HVAC scenarios, to assess the optimal configuration of the system for residential use. The results show that a hybrid system can lower the primary energy consumption up to 28%, thus allowing the employment of renewable energies within the social housing building stock.

1. Introduction

The building sector significantly contributes to primary energy demand and accounts globally for 39% of energy-related carbon dioxide (CO2) emissions [1], issues that European Commission is trying to stem by the agreement of a series of targets to be achieved before 2030: 40% reduction of GHG emissions with respect to 1990 levels; at least 32% share of renewable energy sources and at least 32.5% energy efficiency increase with respect to the initial scenario [2]. In general existing buildings are significantly responsible for the production of greenhouse gases and for energy consumption [3-6], and due to their widespread on the Italian soil with respect to new constructions, whose annual rate is within 0.1–0.2% of the actual building stock [7], they need to be studied in depth, in order to achieve the Community objectives. Comparative analysis conducted on a historical building by ARCHISM and TRNSYS software, pointed out that only some of the nZEBs requirements are met before retrofit interventions, while the rest of the objectives exceed the minimum requirement, due to low envelope performance and low energy system efficiencies [8].

In such cases, primary energy consumption can be reduced thanks to a retrofit of the HVAC system, wherever it is difficult to intervene on the building envelope. In this context, the heat pump represents a promising solution to achieve the objective imposed by the European Commission [9]. Indeed, the use of electricity to power the heat pump reduces the emission of greenhouse gases, furthermore, the heat pump technology encourages the use of energy from renewable sources for its supply, according to the Directive 28/2009/EC [10, 11].

In residential buildings where a single device provides both space heating, cooling and hot water production the air-to-water heat pump has a number of benefits, including low investment costs and easy installations. On the other hand certain characteristics are responsible for some energy saving issues, thus hindering its full spread. During the cold season, the capacity of the device to take heat is reduced, which corresponds to a decrease in the COP, at the same time as the building's maximum energy demand occurs [12]. Another problem is related to the sizing of the heat pump: in general it is designed to meet the maximum load, which occurs in a limited period, while in most of the time the operation takes place with partial load. This oversizing results in a significant reduction in HP's seasonal performance [13].

To ease these drawbacks, a series of scientific studies demonstrated the promising energy performance of different hybrid systems, in which air-source heat pumps are coupled with back-up/alternative heaters connected in parallel or in series [14, 15]. This also avoids the effects of degradation of the frost deposition on the outdoor exchanger, as the heating interruption during defrosting cycles [16, 17], thanks to the other generator's support to the heat pump operation when its heating capacity is insufficient. If the back-up device is an electric resistance, the heaters of the hybrid system have to work in parallel during the whole heating season and the only advantage is the slightly under-sizing of the heat pump, whilst coupling Heat pump and gas boiler the activation can follow an alternative operating mode, with a cut-off temperature selected between the design and the bivalent temperature [18]. Control strategies play a fundamental role in this field [19].

Through Key Performance Indicators (KPIs) it is possible to quantify the energy, environmental and economic performance level of a process [11]: energy-based KPIs allow to evaluate the efficiency of a system and to compare it with that of other monovalent, bivalent and RES-integrated configurations, where thanks to the primary energy conversion factor ($f_{p,i}$) it is possible to cross-check primary energy saving of heaters fed with different energy vectors [18]. Jarre et al. highlight the necessity to take into account that $f_{p,i}$, characteristic of every generation mix, is strongly variable on a hourly basis countries like Italy, characterized by high share of non-programmable renewable sources in the electricity sector [20]. Primary energy savings calculated through hourly values are lower than the ones obtained by using the normative reference value. Efficiency parameters neglect aspects of real thermodynamic processes, where heat losses depend on the thermal level at which the exchange takes place the quality of energy during its transformations, that are influent for the rational use of energy; therefore in [21] the coupling of energy and exergy analysis for assess the performance of systems, especially in cities with high average outdoor temperatures, so where gap between energy and exergy is more consistent, was proposed.

That being said, it is necessary to deepen the problems related to the public social building stock, quite obsolete in terms of energy and with poorly insulated envelopes, due to different economic and technical factors. Very often the inhabitants live in difficult situations, so it is impossible to act on the building envelope and also in the distribution and emission system of thermal energy [22, 23]. Therefore an innovative energy retrofit solution that is worth considering is to adopt a hybrid generation system.

The study explained focuses precisely on existing buildings of this residential typology.

On the basis of a detailed survey of the construction and of both the energy and the domestic hot water systems based on natural gas boiler (NGB) source for heat, a model of the current configuration of the building was created in TRNSYS [24] and validated thanks to the data gathered during on-site measurements. The model therefore allowed the assessment of thermal loads and energy demand of the building. Starting from these results, five improvement scenarios were developed and analyzed, modifying the heat generation system with regard to equipment and control for activation. The purpose of the work is to optimize the energy efficiency of the HVAC centralized system of the ATER existing building through the proposal of monovalent and hybrid solutions with heat pump and gas boiler as heat generators, with the aim of suggesting a common methodology for energy retrofitting [25] applicable to all social housings built around the 80's.

2. Case study

This project focuses on a residential complex owned by ATER (Territorial Housing Agency), built in 1980-85 in Palombara Sabina (DD 2012), a urban area 30 kilometres north of Rome.
The reinforced concrete building hold thirteen flats distributes on three floors and a basement floor with technical rooms and cellars.
All thirteen house were different from each other for border environments, occupancy and surface dispersant. Therefore, it was not possible to identify a typical configuration from the thermal point of view. Consequently in the analysis phase, every single apartment was characterized and studied in detail.

According with the construction techniques of the historical period, the external walls consist of two layers of hollow bricks separated by air and a thin layer of insulating material and covered in plaster (Table 1, partition number 1 and 2 In terms of transparent elements, these are made of single-glazed windows with metal frames without thermal breaks (Table 1, N7). The horizontal structure is made up of reinforced concrete and brick without thermal insulation, except for the attic floor (Table 1, N3-6).

Regarding HVAC, the building is not equipped with a cooling and ventilation system, but instead, a centralized heating system operated by a natural gas boiler (NGB) and radiators from November 1st to March 15th only. In NGB, the maximum heating power input is 69 kW, the maximum and minimum output capacity is 65kW and 51.8 kW, and an efficiency of 0.94 is achieved. The power is modulated based on the boiler outlet temperature set at 80° C. However, steel radiators have different dimensions. Knowing thes, the corresponding powers have been calculated using UNI 10200, Annex D [26].

About DHW, the boiler is not linked to the sanitary water system. Each apartment provides hot water independently by means of an electric boiler.

Table 1: Partition parameters.

N	Partition	Thickness [m]	U-value [W/m^2 K]
1	External Wall type 1	0.30	0.80
2	External Wall type 2	0.25	1.00
3	Roof	0.36	0.64
4	Ceiling above last floor	0.39	0.65
5	Ground floor	0.31	2.27
6	Internal ceiling	0.30	2.27
7	External Window		0.85

Figure 1: Building plan

3. Methodology

In accordance with the flow chart in **Figure 2**, the study consisted of three steps: first, data were collected about geometric, architectural, and thermophysical parameters of the building and HVAC systems; then, TRNSYS models were implemented and validated; and finally, simulated systems were developed and analyzed.

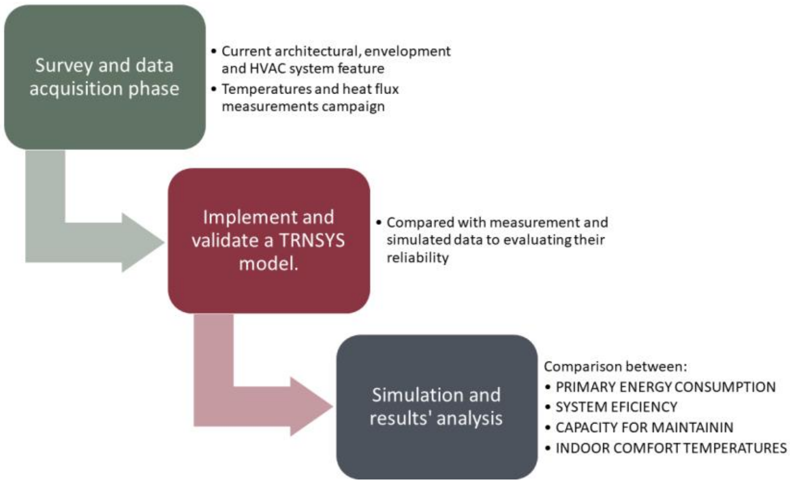

Figure 2: study process flow chart.

A preliminary phase was carried out in the field, for the collection of geometric, architectural and energy system information of the building in its current state, and for measurements of thermophysical parameters in the external and internal environment.
A monitoring campaign was then carried out from 19 to 23 February 2021 for the acquisition of heat flux and indoor and outdoor data. For this purpose, the TESTO 435 heat flow meter was used. Heat fluxes are acquired by means of a heat-flow plate installed inside an apartment at the north-west external wall (Partition type n 1). In parallel, two thermal probes were placed in correspondence to the heat-flow plate, one to each side of the investigated wall, in order to measure both internal and external air temperatures.

The device records thermal transmittance (U, W/m^{2}K) derived from heat fluxes and indoor/outdoor air temperature measurements, applying the Heat-Flow Meter (HFM) method in line with ISO 9869–1 [27] standard.

The measuring device saves thermal transmittance values for each data acquisition step (equal to 10 minutes). Then, the progressive average method was applied to determine the stationary U-value:

$$U - value = \frac{\sum_{j=1}^{N} q_j}{\sum_{j=1}^{N}(T_{i,j} - T_{e,j})} \quad (1)$$

where N represents the overall recorded samples.

In Figure 3, the transmittance (U-value) measured for each step and the average U-value are reported. It can be observed that the measured U-value is equal to 0.804 W/m^{2}K, which is 3% higher than the value calculated applying ISO 6946 [28] to the stratigraphy of the wall, equal to 0.78W/m^{2}K. The percentage difference between HFM and the theoretical values is less than 20%, and then the ISO 9869–1 [27] criterion is satisfied.

A model of the current configuration of the ATER building was created in TRNSYS [9] and validated by means of the data gathered from on-site measurements. As can be seen in Figure 3 and Figure 4 respectively, the physical quantities taken into account for the validation were transmittance of the building envelope and internal temperature.

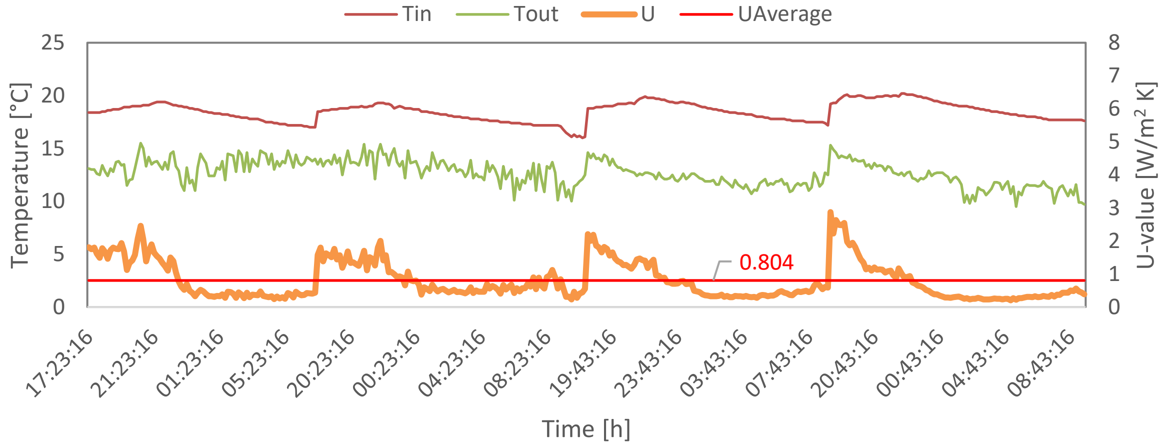

Figure 3: Processing of the data collected by the TESTO 435 multifunction station: internal temperature (Tin, °C); outside temperature (Tout, °C); instantaneous thermal transmittance (U, W/m^{2}K). For the calculation of the transmittance, data with U oscillating around an average value were considered.

The acquired information allowed the TRNSYS model to be implemented and validated. In order to evaluate the reliability of the simulations, the internal air temperatures calculated with the TRNSYS software were compared to the measured ones (Figure 4). It can be seen how the measured internal temperature is almost identical to the one numerically calculated, except for a slight discrepancy in maximum outdoor temperatures. It is shown in Table 2, which reports the uncertainty for the five days of measurement that the average error does not exceed 1.7%.

The abovementioned results show that the mathematical model implemented with TRNSYS is validated.

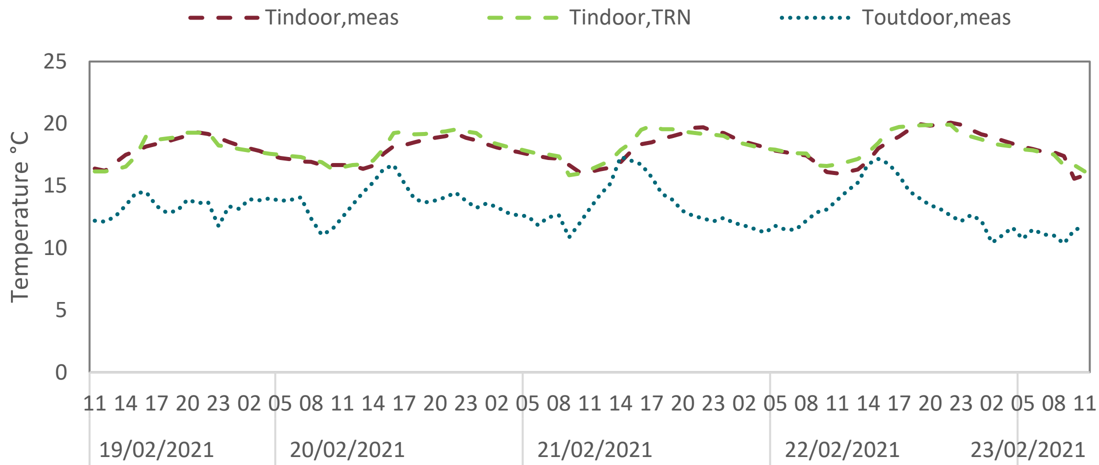

Figure 4: Comparison between measured internal temperature (Tin, meas.) and internal temperature simulated on TRNSYS. The trend of the external temperatures is shown in blue.

Table 2. Summary table with measured and simulated average temperatures and average error for the different measurement days

Date	Average Tin, measured [°C]	Average Tin, simulated [°C]	Average Error %
19/02/2021	18.19	18.14	0.4%
20/02/2021	17.72	17.96	-1.4%

21/02/2021	17.88	18.17	-1.7%
22/02/2021	18.20	18.37	-1.1%
23/02/2021	17.97	17.80	0.8%
Total	17.97	18.12	-0.9%

The model therefore allowed the assessment of thermal loads and energy demand of the building. The thermal energy demand for a typical meteorological year (TMY). The monthly trend is shown in Figure 5.

The maximum thermal power required during the winter is equal to 61 kW, while the cooling power is 64.5 kW. When all the heat loads are summed up, it can be seen that the building has a heating and cooling energy demand per year are respectively: 84.4 MWh and 50.7 MWh.

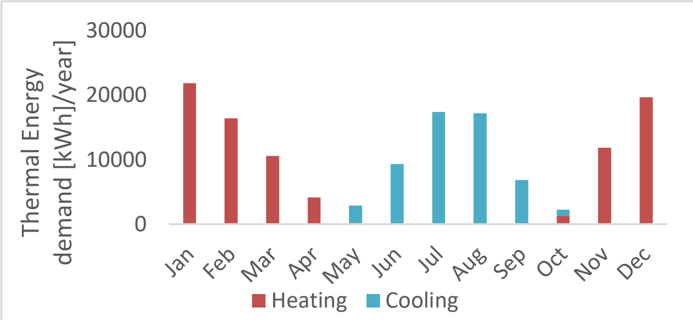

Figure 5: Monthly trend of heat demand in a typical meteoric year (TMY).

By means of Simulation Studio tool, five scenarios were developed, simulating three different heat generators type and modifying the activation and control logic of the system and compared to the existing one, with the aim of improving the energy efficiency of the studied residential building. The outputs were assessed and compared: primary energy consumption, system efficiency, and capacity for maintaining indoor comfort temperature.

In Table 3 the different scenarios adopted are listed; in Figure 6 the layout of the different simulated systems is shown.

The basic scenario, s0, which corresponds to the current state of the building analysed, presents a system powered by a natural gas boiler with a heating capacity of 65kW (nominal power equal to 69kW). The output temperature from the generator is fixed and equal to 80°C, while the activation of the system is regulated giving a specific operation time, from 14 to 22. The terminal units, which remain unchanged, are single or double panel convector radiators.

For the scenarios of group 1 (Figure 6 a), two different control systems are proposed, leaving the system configuration of the s0: in s1.1 the control of switching on and off is done by means of a thermostat for the maintenance of the indoor temperature of 20 ± 0.5 °C.

In s1.2 the control provides in addition to the thermostat as per scenario 1.1, the modulation of the incoming temperature to the radiators in function of the actual thermal demand for the maintenance of the internal temperature of 20 ºC. The thermal power of the boiler is adjustable and the temperature in exit from the boiler is variable according to the conditions internal.

Table 3: Summary of the different heating systems.

Code	Heating generator	Heating capacity	Control system
s0	NGB	65 kW	Time slot (2:00 pm to 10:00 pm)
s1.1	NGB	65 kW	Ambient thermostat (20 ± 0.5 °C)
s1.2	NGB	65 kW	Ambient thermostat (20 ± 0.5 °C) and as function of heating demand
s2.1	AWHP	60 kW	Ambient thermostat (20 ± 0.5 °C)

s2.2	AWHP high temperature	60 kW	Ambient thermostat (20 ± 0.5 °C)
s3.1	NGB and AWHP	65 kW and 60 kW	Ambient thermostat (20 ± 0.5 °C) and as function of heating demand

In the scenarios of group two (s2.1, s2.2; Figure 6 b), the heat generator is an on-off air to water heat pump (AWHP) with a heating capacity equal to 61kW and nominal COP ≥ 3. In s2.1, a traditional AWHP was used and in s2.2, a high-temperature HP was used. The HP is controlled by an ambient thermostat to maintain an indoor temperature of 20 ± 0.5 °C.

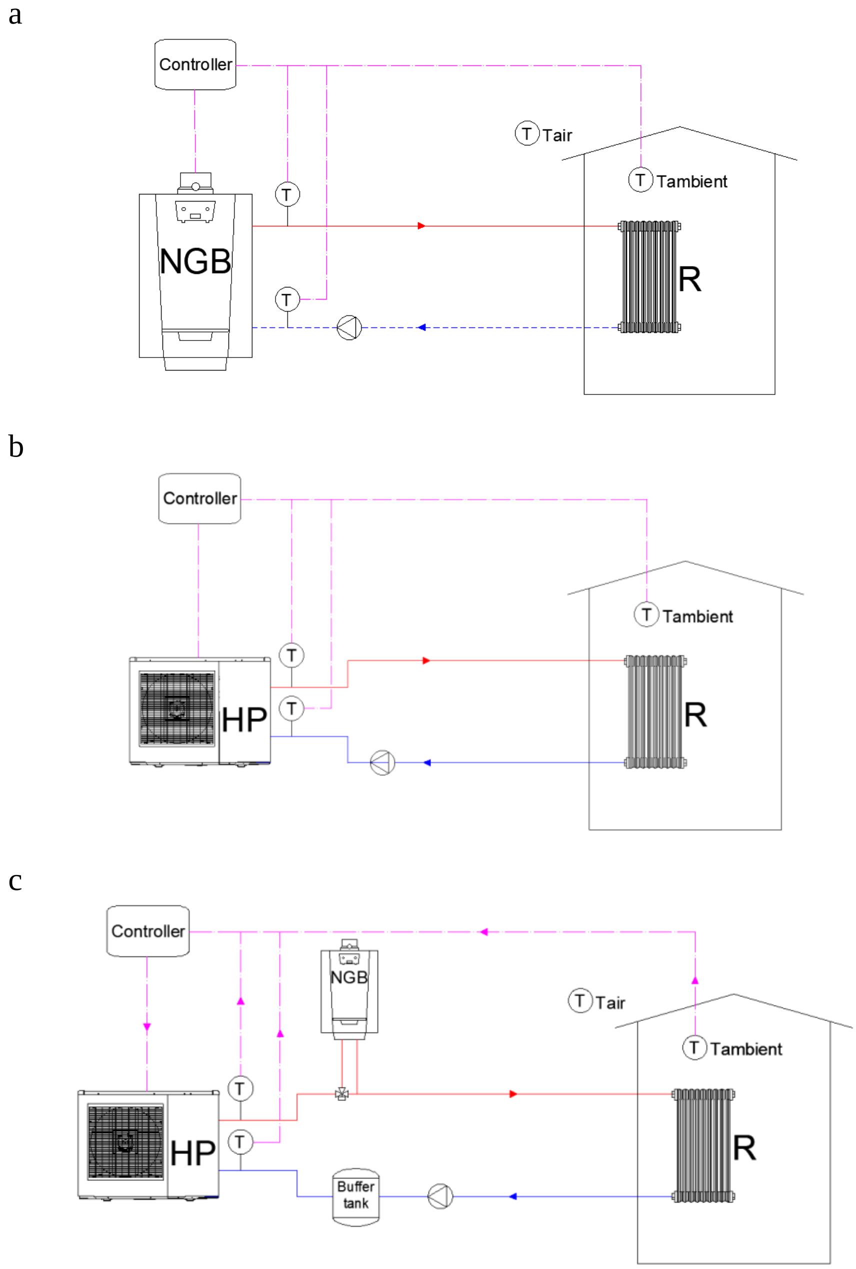

Figure 6: Layout of the scenarios studied: a) natural gas boiler only (s0, s1.1 and s1.2); b) air to water heat pump only (s2.1 and 2.2); c) hybrid system based to AWHP and NGB (a3.1, s3.2 and s3.3).

In the scenario 3.1 (Figure 6 c) a hybrid system (HHP) was used consisting of an air-to-water heat pump (on/off) and the existing natural gas boiler. In this configurations the heat pump and the gas boiler are connected in series and can operate independently of each other. The control system monitors the average internal temperature, and the temperature of the hot water supplied by the generators and compares it with a set point value: when the heat output of the heat pump is lower than the thermal load of the building, the natural gas boiler is activated.

The operating modes of HHp system are governate by the cut-off temperature (Tcut-off) and bivalent temperature (Tbiv) as main parameters related to outdoor temperature (Toutdoor). If $T_{outdoor} < T_{cut\text{-}off}$ the only active heat generator is the methane boiler; if $T_{outdoor} > T_{biv}$ the only active heat generator is the heat pump. The heating system has an alternating operation when $T_{cut\text{-}off} < T_{outdoor} < T_{biv}$ (Figure 7).

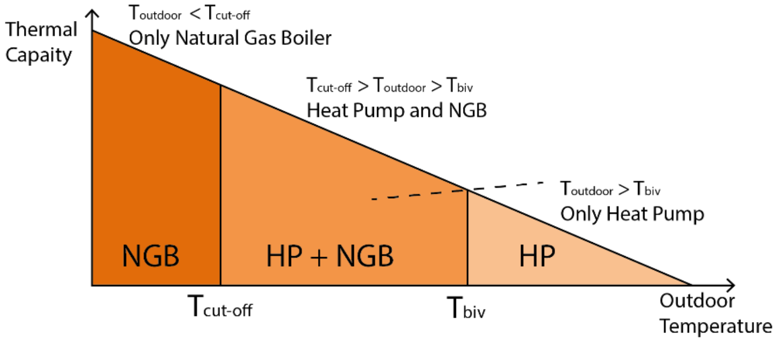

Figure 7: Different operating modes of a hybrid heat pump system.

4. Key Performance Indicators (KPI)

The five KPIs selected below were chosen in order to compare the seasonal energy performance of all the configurations studied where different heat generators were fed with different energy carriers (electricity, EE, and natural gas, gas). Primary energy request (E_P), average seasonal efficiency ($SCOP, \eta_{NGB}$), average seasonal efficiency in relation to primary energy (η_p), average seasonal temperature (T_{indoor}), and standard deviation (σ).

The product between the generator input energy and the primary energy conversion factor ($f_{p,i}$) [29, 30] defined the primary energy demand per generator ($E_{p,HP}$, $E_{p,NGB}$) and total ($E_{p,tot}$) as shown in equation 2-4.

$$E_{P,NGB} = LHV\ Sm^3\ f_{p,NGB} = E_{in,HP}\ f_{p,NGB} \tag{2}$$

$$E_{P,HP} = E_{in,HP}\ f_{p,HP} \tag{3}$$

$$E_{P,tot} = E_{p,NGB} + E_{p,HP} \tag{4}$$

where:

$f_{p,NGB} = Natural\ gas = 1.05$

$f_{p,HP} = electricity = 2.42$

$E_{in,NGB}\ ed\ E_{in,HP}$ are the energy request by the gas boiler (methane) and the heat pump (electricity) respectively, LHV is the lower heating value of methane, Sm^3 = SCM standard cube meter of methane.

It is also important to evaluate the efficiency of the single generator ($\eta_{p,HP}$ and $\eta_{p,NGB}$) and the combined system ($\eta_{p,s}$), expressed as follows from aforementioned indices:

$$\eta_{p,NGB} = \frac{E_{th,build,NGB}}{E_{p.NGB}} \tag{5}$$

$$\eta_{p,HP} = \frac{E_{th,build,HP}}{E_{p.NGB}} \tag{6}$$

$$\eta_{p,s} = \frac{E_{th,\mathrm{tot}}}{E_{p.\mathrm{tot}}} = \frac{E_{th,build,NGB} + E_{th,build,HP}}{E_{p,tot}} \tag{7}$$

where:
$E_{th,build,NGB}$ is the thermal energy transfer rate to building.

Moreover, the average seasonal performance of the individual generator was evaluated. For the natural gas boiler, this being of the standard type (not condensation) is at constant efficiency and equal to 0.94.

While for the Heat Pump was calculated the seasonal coefficient of performance SCOP as the Ratio of Thermal Energy produced ($E_{th,HP}$) and the electricity needed to produce it ($E_{in,HP}$) calculated over the entire heating season:

$$SCOP = \frac{E_{th,HP}}{E_{in,HP}} \tag{8}$$

$$\eta_{NGB} = \frac{E_{th,NGB}}{E_{in,NGB}} \tag{9}$$

To complete the KPI purely energetic described above has been estimated the ability of each system to maintain or not the temperature of internal comfort fixed to 20°C ($T_{indoor,d}$). For this purpose, the average seasonal temperature (T_{indoor}), and standard deviation (σ) were taken into account.

5. Results

Figure 8 show for each scenario the values of the total primary energy requirement ($E_{p,tot}$) calculated according to equation 4, related to the percentage of the primary energy saving. In all scenarios of intervention there is a decrease in the need for primary energy compared to the state of affairs (s0).

In addition, the ability of the different systems to maintain the internal temperature of comfort equal to 20 ºC was evaluated. Figure 9 shows the average indoor temperatures (T_{indoor}) during the heating season (dots) and their position on the basis of primary energy efficiency ($\eta_{p,s}$) calculated according to the equation 7. The error bars represent the dispersion (σ) in relation to the average temperature. With the exception of s0, the average temperature is 20 ºC, the standard deviation is maximum in s1.1 with 0.63 ºC and minimum in s2.2 with 0.18 ºC, in all cases the values are reduced and in accordance with the control settings entered in the simulations (20±0.5 ºC).

From the analysis of the results we have that, with the mere inclusion of a form of control on the natural gas boiler, proportional to the actual demand (s1.1 and s1.2) leads to a decrease in energy consumption in the winter period of 12%, at the same yield ($\eta_{p,s}$), 11% - 12% respectively. The two scenarios (s1.1 and s1.2) differ, however, for the different ability to maintain the comfort temperature inside the building (Figure 9). In s1.1 the average temperature is 20.14±0.6 °C against the 19.9±0.2 °C of the s1.2.

By replacing the boiler with a heat pump (s2.1, s2.2) $E_{p,tot}$ goes from 91.6 MWh (s0) to 74.9 MWh (s2.1) and 78.2 MWh (s2.2) with a decrease of 22% and 19% respectively. The efficiency of the system is maximum and equal to 2.5 (s2.1) and 2.3 (s2.2) depending on the water-heating temperature of the device with an increase of 38% (s2.1) and 27% (s2.2). It is worth to note the different ability of the two considered WAHP generators to maintain the comfort temperature of the indoor spaces: the s2.1 has a performance much higher than the s2.2, but it is not very efficient in winter days, when the external temperature is close to 0°C, with a dispersion equal to 0.34 ºC against 0.18 ºC of s2.2.

The minimum primary energy and maximum yields are achieved with the hybrid system, in particular the s3.1 has a decrease of $E_{p,tot}$ equal to 28% and an increase in efficiency equal to 54%, in compliance with [18]. Combining the energy data and the internal temperature values representative of the thermal well-being, scenario s3.1 turns out to be the optimal one, with an efficiency of 2.4, and a temperature oscillation of 20°C±0.26 ºC.

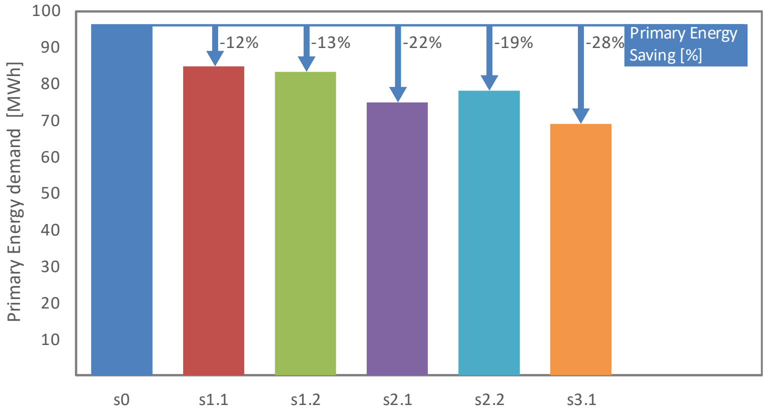

Figure 8: (Ep,tot) Total primary energy calculate according to equation 3 for each heating layout and percentage of the primary energy saving of different scenarios related to the s0

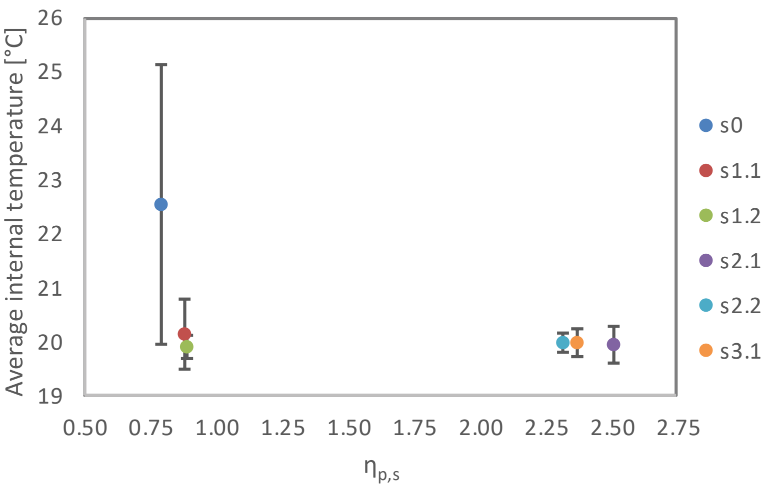

Figure 9: Comparison between system efficiency ($\eta_{p,tot,s}$) and the indoor average temperature (T_{indoor}). The error bars are the scenarios' standard deviation (σ).

6. Conclusion

A comparison of different heating systems was carried out in this study in order to improve energy efficiency and maintain the existing distribution and supply systems.

Six dynamic simulations were performed by TRNSYS to conduct the analysis. Based on on-site measurements, a numerical model was first created and validated, followed by a calculation of building thermal energy demand for a typical meteorological year (TMY). An analysis of the scenarios was conducted using three types of heating generation: only natural gas boiler (s0, s1.1, and s1.2), only air-to-water heat pump (s2.1 and s2.2), and a bivalent system (s3.1).

It was determined which configuration reduced primary energy consumption most efficiently when compared monovalent, with and without the heat pump, and bivalent scenarios.

The results show that, when it is not possible to alter the building envelope, hybrid systems can achieve substantial energy savings. This is despite the low efficiency of the existing buildings and the high thermal conductivity of their external walls. In terms of primary energy demand, a reduction of 28% is possible.

The aim of the project was to develop a high-efficiency energy system for social housing without performing any work on the distribution and supply system. Moreover, the use of an electrical heating generator has a high potential and could be integrated with renewable energy sources. Further

improvements concern the possibility of integrating a photovoltaic panel with cooling, which can meet the electrical and thermal energy demands with on-site renewable energy generation.
Project goals included developing a high-efficiency energy system without enlarging distribution and supply plant. Moreover, electrical heating generators are capable of integrating with renewable energy sources and have a high potential. A further improvement would be the integration of a photovoltaic panel with cooling, which would provide electricity and thermal energy with on-site renewable sources.

7. Acknowledgments

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8. Nomenclature

U-value	W/m^2 K	Thermal transmittance	$T_{indoor,d}$	°C	Design building Indoor temperature (20°C)
$T_{in,w,HP}$	°C	Temperature of intel water to heat pump	T_{supply}	°C	Supply temperature of the heating system
$T_{air,in,HP}$	°C	Temperature of intel air to heat pump	T_{retur}	°C	Return temperature of the heating system
$E_{in,gen}$	kWh	Energy consumed by the i-th heating generator	T_{biv}	°C	Bivalent temperature
$E_{th,gen}$	kWh	Thermal energy delivered to the liquid stream by the i-th heating generator	$T_{cut\text{-}off}$	°C	Cut-off Temperature
$E_{th,build}$	kWh	Thermal energy transfer rate to building	η_{NGB}	-	Boiler efficiency
$E_{p,tot}$	kWh	Primary energy consumption	$\eta_{p,s}$	-	Primary energy system efficiency
T_{indoor}	°C	Average building Indoor temperature	$f_{p,i}$		Primary energy conversion factor
$T_{outdoor}$	°C	Outdoor dry bulb temperature			

Subscript and Acronyms

NGB	Natural gas boiler	TMY	Typical meteorological year
rad	Radiators	CH	Centralized heating
FC	Fan coil	DHW	Domestic hot water
HP	Heat pump	AWHP	Air to water heat pump

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