Energy building retrofitting of a multifamily house: a case study

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Abstract

The residential sector contributes largely to energy consumption in Europe: around 40% of the EU energy use (RHC-ETP, 2011).

For a massive reduction of the energy consumption in the European residential sector, a common practice is the retrofitting of existing buildings. In this context, multifamily houses (MFHs) are considered to be easier to retrofit, partly because their exteriors are more uniform than single-family houses' - which makes external insulation and glazing replacement easier to install - and partly because each building contains multiple dwellings - therefore a single action can affect more living area.

The purpose of this paper is to report on the design phase of a multifamily house located in Madrid, Spain. The refurbishment concerns the installation of both passive and active solutions. In particular, transmissions through the envelope are reduced by the addition of an insulation layer and new windows. DHW production, space heating and cooling are guaranteed by an air-to-water heat pump. Heating demand and Domestic Hot Water (DHW) production are also partially covered by solar thermal panels installed on the parapet of the building.

The impact of the retrofitting measures on the energy consumption have been assessed starting from energy audit data, going through modelling and simulating the building's envelope before and after the retrofit, and finally analysing the building and energy plant together.

The simulation work shows a set of integrated measures suitable to achieve a primary energy consumption for heating, cooling and domestic hot water, lower than 50 kWh/m²y.

1. Introduction

The total residential floor area in the 27 European countries is approximately 17.6 billion m². Of this 15.1 billion m² is estimated to be heated. For the sake of simplicity, the residential building stock can be divided in two main typologies: single-family house (SFH), with a single dwelling unit within its own building and multi-family house (MFH) where a dwelling is in a multi-occupancy building. SFHs and MFHs distribution is different across the Europe. Denmark, Ireland, the Netherlands and the United Kingdom have the highest proportions of SFHs (all above 70%) whereas Estonia, Italy, Latvia and Spain have the lowest proportions of SFHs (all below 40%). The age distribution of the residential building stock varies from country to country, but the age of both single and multi-family houses is broadly similar across Europe with a growth rate peak between the 1950s and 1970s. The rate of new builds has been slowing since the 1970s, with a strong reduction occurring after 2000. Spain had higher than average construction during 1971-1980 and after 2000.

For a massive reduction of the energy consumption in the European residential sector, a great retrofitting of existing buildings is needed. In this context, MFHs are often thought to be more cost effective targets for retrofit, because of the consistent architecture and economies of scale on a large block of apartments. Moreover, they are considered to be easier to retrofit because their exteriors are more uniform than single-family houses - which makes external insulation or replacement glazing easier to install (Birchall S. et al, 2014).

In this sense, the purpose of this work is to present the renovation process applied to a demo case, which uses non-invasive techniques and aims to reduce the total amount of energy consumption.

The methodology foresees the use of numerical models to assess the actual building demands and the assessed energy savings.
The building presented in the following is a MFH of the 1960s located in Madrid. In line with the above observations, this kind of building can be considered as representative of a big portion of the Spanish residential building stock.
The building is located in the suburbs of Madrid and it is composed of two linear blocks for a total of twenty dwellings (50 m² living area each) on five floors. In this study, only one of the two has been analysed (in the red circle in Fig.1).

Fig. 1 – North façade of the demo case–in the red circle the analysed building

The refurbishment concerns the installation of both passive and active solutions. In particular, transmissions through the envelope are reduced by the addition of an insulation layer and new low transmittance windows. DHW production, space heating and cooling are guaranteed by an air-to-water heat pump. Heating demand and Domestic Hot Water (DHW) production are also partially covered by solar thermal panels installed on the parapet of the building.

2. Methodology

The impact of the retrofitting measures on the energy consumption have been assessed through the following steps:
1) building energy audit for the definition of the building characteristics and consumptions;
2) modelling of the existing building's envelope and calculation of the building demands;
3) modelling of the renovated building's envelope and assessment of the building demands;
4) modelling of the thermal plant and simulation of the whole system (building + energy system + control strategies);
5) planning of the renovated case by using non-invasive techniques, allowing the owners to live in the building while the renovation takes place.
Simulations have been run in the dynamic environment of TRNSYS Simulation Studio (Klein S.A., 2009), while the geometry of the building has been developed in Google SketchUp and set up in TRNBuild.

2.1 Building energy audit

The energy audit concerns building characteristics, uses and energy consumption. Information comes from technicians and surveys distributed through the tenants. Daily and yearly profiles have been defined for the occupation and electric use, distinguishing between workdays and weekends. Some examples of these schedules are showed in Fig. 2 and Fig. 3.

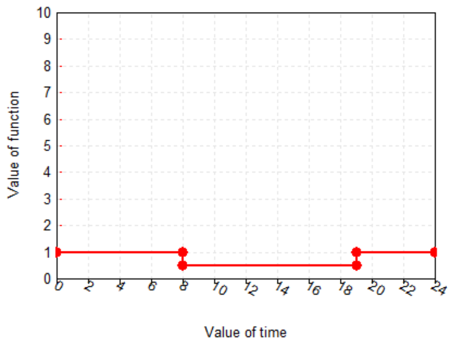

Fig. 2 – Schedule of occupancy during the weekdays

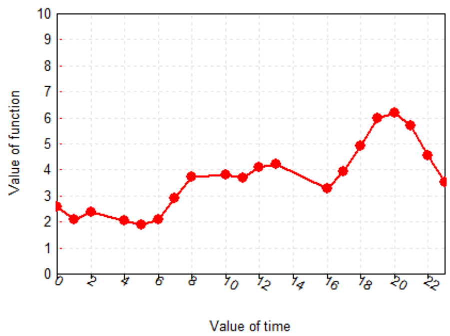

Fig. 3 – Use of electric devices during the weekdays

Thermal characteristics have been calculated for the envelope elements: external walls, roof, ground floor, windows, internal partitions, adjacent walls (towards the second part of the building block). Thickness and heat transfer coefficient (U_{value}) of opaque and glazed surfaces are reported in Table 1 and 2.

Table 1 – Thermal characteristics of the envelope

Wall	Thickness	Heat transfer coefficient (U_{value})
	[m]	[W/m²K]
External wall 1	0.35	1.51
External wall 2	0.32	1.57
Roof	0.68	1.51
Ground floor	0.27	2.19
Adjacent wall	0.25	1.54

Table 2 – Window characteristics

Window	$U_{value\_glazing}$	U_{value_frame}	$g_{value\_glazing}$
	[W/m²K]	[W/m²K]	[-]
Window single glazed	6.11	5.88	0.81

The following figures (Fig.4 and Fig. 5) show the wall construction for the external wall and ground floor. The latter has an aerated cavity below the concrete layer. In the numerical model, the air cavity has been not modelled; however, the outer surface bounds with a temperature that takes into account the presence of it (UNI EN 13370, 2008).

Fig. 4 – Drawing of the external wall construction

Fig. 5 – Drawing of the ground floor construction

The existing case does not have any insulation for the external surfaces. For more detail, please refer to D7.1b P15 Energy Audit Madrid (García J. et al., 2014).

2.2 Building - existing case

The model of the existing envelope has been defined following characteristics and boundary conditions defined in the Energy Audit. For some physical and geometrical features, a parametric analysis has been carried out in order to investigate the effect they have on the building loads assessment and simulation run time. For the sake of relevance, only the results of the study above mentioned are reported. The whole work can be found in (García J. et al., 2014 p. 40-53).

First of all, as this model is used afterwards in an integrated environment, where energy and distribution systems and control strategy are implemented together, it has been designed to limit the computational effort.

Starting from a first model elaborated using a common best practice approach (IBPSA-USA, 2012), variations on the definition of the number of floors or zones, thermal capacitance, internal walls, internal or external surface measures and thermal bridges have been applied one per time.

The first investigation has involved the definition of the optimal number of zones for truthful results and limited computational effort. A good trade-off between developing one thermal zone per room rather than one per floor is to create one zone per apartment or per orientation. This last case, in fact, takes into account also the distribution of temperature inside the apartment due to a different exposition (see Fig.6).

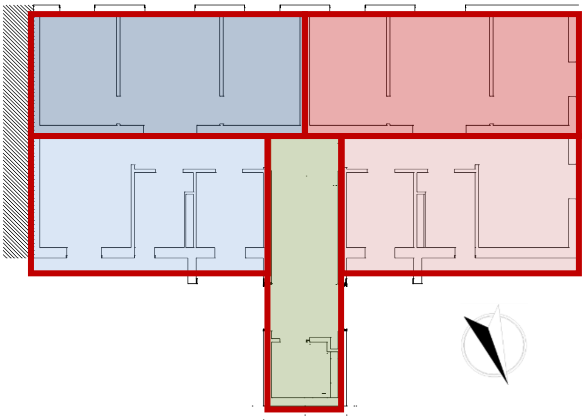

Fig. 6 – Thermal zoning of a typical floor

In case of buildings with more than 3 floors, a reasonable simplification consists of relating in-between floor behaviour to a unique intermediate floor. Loads and demands of this storey are than accounted also for the others.

Considerations have been carried out also on the thermal air capacitance value: it plays a role mainly in the distribution of internal temperature through the day; in fact it does not influence loads neither demands assessment. As a consequence, the thermal air capacitance has an effect on the comfort levels: models with higher thermal mass have smoother temperature profiles with respect to models with low thermal capacitance up to reduce the peak temperature of around 1°C, and to shift the loads from 1 to 5 hours.

The definition of the building geometry has been delineated in the SketchUp tool. For the sake of simplicity, the plant of the renovated case has been developed and used for the existing case too, in order to compare results referred to the same volume. The definition of the geometry with this tool entails a-dimensional surfaces. Consequently, these can be delineated by means of internal edge, external edge or centreline measures.

The surface area influences transmission losses, therefore to assess the approximation due to the use of one of the above measurements, comparisons on the heating and cooling demands have been carried out. When internal edges or external edges are used, geometrical thermal bridges have been modelled, too. The linear transmission coefficient Ψ can be calculated by default values from norms or by software based on Finite Elements Method. In the first case, a high uncertainty can occur; in the second case, expertise and time consuming in the definition phase can be needed. In this sense, a simplification, which however maintains a real behaviour, consists of using the centreline measures.

In those cases where more than one thermal zone is modelled for each dwelling, an air coupling of adjacent rooms shall be accounted for. Simulations had shown that the convective air coupling between zones has not a relevant influence on building loads and energy demands, whereas it affects internal temperature distribution. The most evident effect is that a more homogeneous temperature distribution occurs within the same flat, but simulation runtime can triple. Air coupling is therefore useful when a thermal comfort study is carried out, but for maintaining limited computational effort, it can be neglected when only demands are to be assessed.

In light of the above considerations, the geometrical model of the actual building has been defined with centreline measures; one zone per orientation per dwelling; first, last and an intermediate floor accounting for the all in-between floors. In this first phase, no coupling has been used and thermal capacitance of air plus internal walls has been fixed for each zone.

Other boundary conditions implemented in the model and used for both existing and renovated case are shown in the Table 3.

Table 3 – Boundary conditions used in the building model

Parameter	Units	Value
Electrical gains	[W/m²]	1.44
Heating set temperature	[°C]	20
Cooling set temperature	[°C]	25
Infiltration rate	[vol/hr]	0.15
Ventilation rate	[vol/hr]	0.30

Using the above explained building model and boundary conditions, simulation showed the results seen in the following Table 4.

Table 4– Heating and cooling demands and peak loads for the ground floor, second floor and last floor, referred to the actual case

Zone	Heat demand	Cool demand	Heat peak power	Cool peak power
	[kWh/m²y]	[kWh/m²y]	[W/m²]	[W/m²]
GF	151	18	72	38
2F	93	30	55	44
4F	151	35	85	51
BUI	116	29	85	51

To date, each dwelling has its own and peculiar thermal system installed. DHW and heating are provided to all the dwellings, while just three of them are provided with cooling. The energy resource varies for each dwelling: the most common for DHW is natural gas; for heating, it varies between natural gas and electricity; electricity is also used for to run mono-split units. Some dwellings have butane gas bottles for DHW and heating. Those dwellings with gas boiler for heating have hot water radiators for the distribution system, while the rest of them are provided with independent electric radiators or butane heaters.
Due to the complexity of the heating systems, generation and distribution systems have not modelled for the existing case. For the sake of simplicity, energy consumption has been calculated from demands.

2.3 Building - renovated case

In general, renovation measures on existing buildings can involve both passive and active solutions. On the one hand, the attempt is to reduce demands and loads, on the other the improvement of heating and cooling systems efficiency is focused. In the demo case, both solutions are foreseen.
The high transmission losses due to high transmittance values through external walls, roof and ground floor are reduced thanks to the installation of an insulation layer of 8 (on the external walls) and 6 cm (on the roof and ground floor). The existing roof consists of an air cavity of 40 cm above the last ceiling, closed by a system of small vaults and covered by ceramics and a waterproof layer. During the renovation work, the air cavity is substituted with the insulation layer, and is covered by ceramics.
In this way, the building air-tightness has also been improved. Moreover, new windows with low emissivity are installed externally, in addition to the existent ones, in order to reduce the impact of the installation work on the tenants.
The envelope model of the renovated case is based on the existing case, with the addition of the retrofit measures (insulation and windows).
The implementation of these passive solutions has the effect of a strong reduction in the heating demand, of around 83%, and a slighter decrease in cooling demands of around 16%. Due to the higher thermal capacity of the building after the renovation, the decrease in cooling demand is lower than the one for the heating, despite the use of external shadings.
Looking at the peak loads, the maximum heating load decreases by 66% and the cooling load by 47% (see Table 5). Despite the small reduction of cooling demand in the renovated case, the reduction to almost 50% of the peak load implies a smaller installed chiller capacity.

Table 5 – Heating and cooling demands and peak loads for the ground floor (GF), second floor (2F) and last floor (4F), referred to the renovated case

	Heat Demand [kWh/m² y]	Cool Demand [kWh/m² y]	Heat peak power [W/m²]	Cool peak power [W/m²]
GF	29	20	25	25
2F	14	25	20	24
4F	31	24	29	27
BUI	**20**	**24**	**29**	**27**

After the renovation, a centralized system covers the heating and domestic hot water preparation. Moreover, the new A/W heat pump of 15 kW provides cooling to all dwellings. Solar collectors installed on the parapet, for a total of 28m², contribute to the heating and domestic hot water preparation.

A new low-temperature heating distribution system is installed and, for this purpose, radiant ceilings allow for a temperature under 30-35°C.

In addition, shading elements are foreseen to be installed onto the windows at the south and west oriented façade, in order to avoid overheating in summer.

In the renovation, piping is distributed outside the north façade, embedded in the insulation, in order to reduce the heat losses.

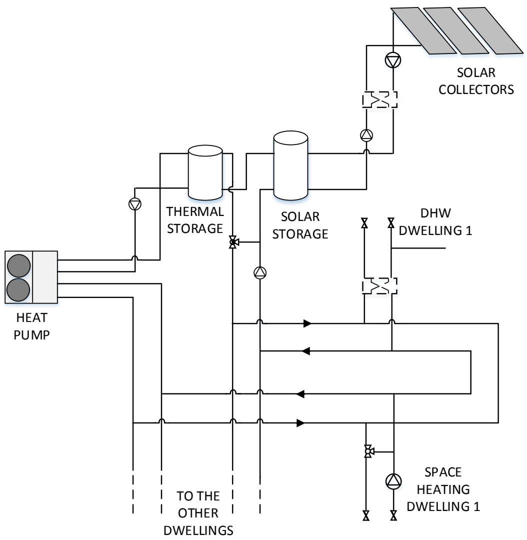

Fig. 7 – Sketch of the TRNSYS deck: building + generation and distribution system + control system

2.4 Simulation of building and energy system

As already mentioned, the building and system numerical models have been developed and simulated in the TRNSYS environment. The envelope model of the renovated case has been integrated with the heating and cooling system and relative control. Each element of the new heating and cooling system has been modelled and thermal and electric consumption calculated.

The TRNSYS deck includes all the hydronic and electronic components of the generation and distribution systems. In particular, type 832 (Haller M., 2013) is used for the 28 m² of flat plate solar collectors oriented to the south façade and with a slope of 90°. The 15 kW heat pump is modelled with type 927; it reads a performance map, which gives thermal and electrical powers depending on the inlet temperatures and mass flows on the source and load sides. Solar collectors feed a 1000 l of stratified thermal storage; the latter charges another thermal storage of 500 l. The DHW preparation is therefore covered by solar energy and heat pump in case of too low temperature inside the smaller storage. Space heating can be provided directly by the heat pump or by solar energy through the second storage. The heat pump provides cooling during the summer season.

The profiles for the DHW demand have been generated for a number of inhabitants of the building using a stochastic model developed by researchers at Uppsala University (Widén et al., 2010). These profiles have a day-to-day variation over the whole year; they are also smoother and more realistic than an aggregate of only one repeated for all the apartments.

The distribution system consists of radiant ceilings. They are characterized by an aluminium structure with embedded copper pipes. The standard module is 1.2 x 2.4 x 0.02 m and they have been installed in order to partially cover the ceiling of each room.

The TRNSYS deck has been built gathering several “subdecks” which represent a technology or device. The subdecks used in this system are:

- WEATHER FILE with external conditions for Madrid (Meteonorm, 2013)
- FLAT PLATE COLLECTORS composed by the solar collectors type and pipes for the distribution system losses;
- STORAGE TANK for the three thermal storages;
- AIR-TO-WATER HEAT PUMP connected to a performance map and with an internal control to regulate the winter or summer working modes;
- RADIANT CEILINGS linked to each thermal zone of the building as wall gain;
- HYDRAULIC MODULE which contains pumps, valves and heat exchangers;
- MAIN CONTROL, which regulates the whole functioning of the system;
- BUILDING MODEL.

The main control regulates all the parts of the system in order to guarantee the thermal comfort inside the building and the DHW preparation. It receives information from all the subdecks and gives control signals to all the active components.

Table 6 – Heating and cooling demands calculated ideally and with the whole system (building + energy plant)

	Heating demand [kWh/m² y]	**Cooling demand** [kWh/m² y]
Ideally	**20**	**24**
Whole	**21**	**31**

Table 7 – Performance figures of the renovated building + energy plant system

	SF DHW [%]	**SF heat** [%]	**SPF** [$kWh_{UE}/m^2y/ kWh_{FE}/m^2y$]	**PE** [kWh/m^2y]
YEARLY	38%	15%	4,3	47

Simulations have been run following the requirements foreseen in the design and sizing phase. Further optimization of components size and control strategies are foreseen, but not included in this paper.
Table 6 compares the building demands for heating and cooling calculated ideally and with the modelled system. The temperature set points for heating and cooling in the ideally case have been fixed at 20 and 25°C respectively; while for the whole system, hysteresis between 19.5-20°C for winter and 24.5-25°C for summer have been defined. Due to the difference of the set points, differences on the Table 6 results comes up, especially for the summer case.
In line with the aim of the study to reach a total Primary Energy consumption of 50 kWh/m^2y, it is interesting to have a look at Table 7. In particular, the renovated case shows a Solar Fraction (SF) (Malencovic I., 2012) of 15% for the heating and 38% for the yearly DHW production. With respect to the installed system, the low values of SF for the DHW preparation is due to the higher DHW consumption. An average of 2.4 people is usually considered to live in a dwelling of 50 m². Besides in our case, there are some apartments where up to 5 people live, consequently there is a higher DHW demand.
The Seasonal Performance Factor (SPF) (defined in Malencovic I., 2012), that represents the useful energy compared to the final energy, amounts to 3.6 and 5.1 respectively in the winter and summer season. The high values of SPF are related to the decrease of the building demands and, above all, the efficient use of renewable sources (air and solar sources).
Finally, the total Primary Energy (PE) consumption for space heating, cooling and DHW production amounts to 47 kWh/m^2y. For this calculation, a Primary Energy Factor (PEF) for the electricity of 2.461 has been used (IDEA, 2014).

2.5 Non-invasive techniques

In the demo case, the retrofit takes place together with some structural works for the whole building. This strategy allows reducing the costs for the renovation because coupled with other needed maintenance activities.
Passive solutions are mainly installed externally on the façade in order not to affect the daily-users' life. Piping has been, in fact, developed along the façade as well as the insulation. Existing windows are not replaced and new ones are installed externally.
With regard to the active solutions, heat pump, storages and solar collectors are installed on the roof and parapet. The only work within the dwelling consists in installing piping and radiant ceilings.

3. Conclusions

The significant energy consumption related to the residential sector suggests a massive refurbishment of the existing buildings all over the Europe needs to be undertaken. In this sense, a structured approach for the entire process may help to indentify the best retrofitting solutions, assess the new building consumption and foresee those interventions with low impact on the owners' daily life.

In this paper, a methodology for building refurbishment is applied on a multifamily house. An energy audit on the existing building gave all needed information on wall construction and internal gains.

The modelling of the existing building indentifies the base case for further improvements on the building envelope and system performances.

A parametric analysis has been carried out in this work in order to create a building model which is reliable, but at the same time, manageable within the simulation of the whole system. The final building model therefore contains 3 out of 5 floors, where the in-between represents all the intermediate storeys. One zone per orientation (north-south) per dwelling has been modeled in order to take into account the different internal loads.

Renovation measures on the existing building consist of the addition of an insulation layer on the external walls, roof and ground floor and of new windows externally to the existing ones. These actions help to reduce the building heating demand by up to 83% and the cooling demand by 16%. The energy system described allows us to reach a total PE consumption of 47 kWh/m²y.

The implementation of these renovation measures shows building consumption can be drastically reduced with non-invasive techniques.

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