BLOCK LEVEL STUDY AND SIMULATION FOR RESIDENTIAL RETROFITTING

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ABSTRACT

Being aware that energy refurbishment is an activity that not only has a positive environmental impact but also activating the local economy, the City of Santa Coloma de Gramenet (Barcelona, Spain) decided to promote it for homes via introducing the Energy Services Companies model. Therefore, it has been commissioned an energy audit for multi-family housing.

The aim of the paper is to provide an estimation of energy and economic savings entailed in a global block scale intervention, opening the way to new models of energy management, focused on the Mediterranean region. The results are based on detailed simulation, of selected building typologies in the block and estimation of integrated renewable energy and efficient systems.

INTRODUCTION

Energy management of buildings through Energy Service Companies (ESCO) has proven to be a powerful way to reduce energy consumption in buildings. Energy audits are being an essential tool prior to these energy saving measures.

Currently the ESCO management model is spreading to industry and commercial buildings, but needs to find the right circumstances to intervene also in the residential sector, which is an important part of the building stock. There is specially a great potential regarding multi-family housing in Mediterranean region, although the energy use intensity is low and several technical , cultural and financial barriers are present (Ortiz , Salom, & Cubí, 2012).

One of the barriers to the ESCO model is the difficulty to predict the actual effectiveness of the measures taken over the building due to the disparity of equipment types and occupants' behaviour. To solve this, the audit acts at once on a large enough number of users, so that the consumption profile of the group is as close as possible to the average, and consequently as much predictable as possible. A whole existing multi-family block with 534 dwellings has been chosen as the object of the audit. The block is representative of most of the building stock in the area, as the long-term objective is to apply the results to the rest of the city.

The first part of the work was to determine the energy profiles of users, by corroborating statistics with block's user data, obtained via direct survey and energy bills consultation. Consumption was determined according to the different energy sources and the degree of implementation of equipment, type of equipment and the relationship between consumption and the type of building.

On the other hand, building's envelope features have been collected and analysed. With that information, some representative models have been built and simulated using TRNSYS (SEL, 2012).

The objective of simulations was to predict the heating and cooling demands of representative housing types. Later, models were simulated adding different envelope renovation hypothesis to determine the impact on the demand for heating and cooling in each case.

Envelope renovation proposals have been combined with actions on existing facilities and integration of renewable energy proposals. The large-scale actions provide better cost-effective solutions than action for a single building.

METHODOLOGY

The methodology used in this study refines at block level the urban scale energy modelling methodology described by (Ivancic, Lao , Salom , & Pascual, 2004) and applied originally to the city of Barcelona. This methodology has been applied to the city of Santa Coloma de Gramenet to study the building typologies and energy consumption on a city level (Barcelona Regional , 2012). Based on the results of the study, one representative residential block composed by 43 buildings and 534 dwellings has been selected.

Dwelling typologies identification and building characteristics have been done through detailed analysis of blue-prints from all the buildings and inspections on the field. Thermography pictures were taken in order to complement building constructive data, obtaining coherent results.

Nine per cent of the dwellings have been surveyed in order to obtain information on the next aspects:

- occupation and use profiles;
- energy consumer appliances characterization and penetration level;
- thermal, lighting and acoustic comfort levels;
- use of passive strategies;
- dwellings' conservation level.

All the surveyed dwellings were asked to provide annual energy consumption data. This has been complemented with detailed energy bills information (both electricity and natural gas) from thirteen dwellings. Users' habits in summer towards thermal comfort and use of ventilation strategies were checked by monitoring two dwellings during one week.

An average occupation and energy use profile has been extracted from the survey results. It has been validated by checking its coherence with other studies developed at local and national (IDAE, 2011), (Cipriano, Martí, Carbonell, & Pérez, 2010).

Through collected data different block's representative dwelling models have been elaborated and its thermal behaviour has been simulated, with the aim to quantify theoretical energy loads for heating and cooling. Climatic data were collected and analysed from the nearest meteorological station.

TRNSYS 17 has been the program used for simulation. TrnBuild and TRNSYS 3D plug-in for Google Sketchup have been used for building and surroundings geometrical definition.

Three passive retrofitting scenarios have been proposed regarding envelope's refurbishment, solar shading and ventilation strategies. Simulation has been run on improved models in order to characterize each measure's efficacy and to determine to the reduction of heating and cooling loads.

On the other hand, different scenarios have been developed based on energy generation systems and renewable energy sources, to be implemented over the passive refurbished scenario. Energy savings and economical balance have been calculated on these integrated scenarios, which include demand reduction, high efficient systems and use of renewable energy sources.

The aim of the study is to have solid quantification representing the energy consumption and different alternatives of energy refurbishment at block level. These data should assist the city council, ESCOs and owners as a solid basis to design and develop strategies and projects for the retrofitting at block level and to replicate them to the rest of the city.

DESCRIPTION OF THE HIPOTHESIS, MODELS AND SIMULATION

Multi-family block features

This study reaches 31 out of the 43 block's buildings. All of them are attached, multi-family buildings, with 4 to 6 floors (including ground floor). 84% of these were built between 1965 and 1975, matching the highest population growing and urban expansion of the region, and so they have very similar constructive typologies: concrete structure with ceramic non-insulated walls, terraced flat roofs composed by a concrete floor and ceramic tiles finishing, non-insulated, and single glass windows. It is important to state that most of the dwellings were built before the existence of any building thermal regulation (first Spanish one was established in 1979).

Most of façades are oriented South-west (facing Salzereda avenue and Besòs river, which is an exposed orientation), and Northeast (facing St. Joaquim street, on a shadier situation). There are also secondary façades facing block's courtyard, with the same orientations, and small size inner ventilation atriums in each building. Heated area for each dwelling varies from 50 to 70 m^2.

Typology determination is of a special relevance: shape and compacity of the building, external envelope's area regards dwelling surface, atriums location as cross-ventilation elements on summer, determine building's thermal behaviour together with envelope's constructive characteristics. Two main formal typologies have been identified: with two dwellings per floor and with four dwellings per floor. In addition, two different façade composition types can be distinguished, depending on balconies existence and glass surface proportion. On a constructive level, two different façades are mainly detected (15cm thick ceramic wall, and 30cm thick cavity wall).

Simulation models have been built based on specific building from the block which are representatives of the main typologies. Models to be simulated include one building's floor, based on real buildings number 38 (2 dwellings per floor, low glass surface proportion and 15cm wall) and number 39 (4 dwellings per floor, 30cm façade with balconies).

These models have been placed on the two main orientations. A third model is developed for North-South façade, based on number 39 typology.

In addition, two variants of each model have been developed, whether the model is placed on a standard floor or it refers to an under roof floor.

Figure 1.Location of models on block plan

Heating and cooling demand in Base Scenario

3D building detailed models (4-6 thermal zones per flat) have been developed with multizone building tools in TRNSYS, featuring parameters as follows:

- Envelope's constructive characteristics depending on the two typologies detected.
- Surroundings and own building's shades according to 3D location model.
- Occupation profiles, use of light and equipment according to statistical results based on developed surveys.
- Ventilation rates according to statistical data.
- Comfort parameters according to national regulation requirements.

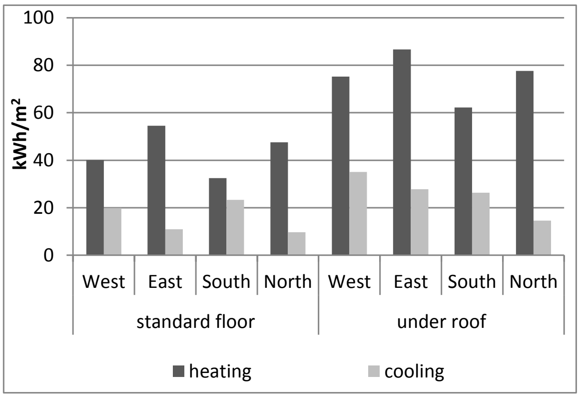


Figure 2.Yearly heating and cooling demands for model 39

After this first simulation, which results are depicted in Figure 2 some trends of thermal behaviour can be deduced:

- Heating demand is always higher than cooling demand in all the analysed situations
- Orientation and surrounding shading elements: comparing the same model placed in both main orientations, different demand oscillations can be observed. Higher values are located in higher glass surfaced façade dwellings.
- Roof exposition: when speaking of poor insulated roofs as the ones in this study, demand difference between a standard floor and an under roof floor vary significantly.

In order to estimate a global heating and cooling demand for the whole block, simulation results have been extrapolated to all the existent buildings, according to characteristics detected in exhaustive data collection

Table 1 summarizes the results for energy demand, both for the entire block and for an average dwelling.

Table 1.Global yearly energy loads

	kWh/y	Average kWh/dw/y	Average kWh/m^2/y
Heating	1 489 625	2 790	48.56
Cooling	464 172	869	15.13

Domestic hot water demand in Base Scenario

According to the references (Gobierno de España, 2009) and (Cerrillo, 2012) the domestic hot water consumption is estimated in 20 litres/person/day. This value results on 964 kWh/dw/y and total demand of 514 905 kWh/y. The survey provides information about the penetration of this use in 98 % of the dwellings. All of them have a boiler, 86 %, which are fuelled by natural gas, and 12 %, which are fuelled by butane.

Lighting and domestic appliances consumption in Base Scenario

The lighting and domestic appliances consumption is based mainly on the survey data, data of regional studies about performance of energy in domestic use (Barcelona Regional, 2006), (Cipriano, Martí, Carbonell, & Pérez, 2010), and the national project SEHC-SPAHOUSEC (IDAE, 2011). SEHC-SPAHOUSEC aims to give a detailed overview about the energy consumption in Spanish houses based on monitoring, survey and total energy balance.

In case of appliances, main parameters are the *penetration ratio* of equipment per dwelling as well as the *multi-equipment ratio* (average number of appliances per dwelling). Both values are based on survey data. Most of the appliances are driven by electricity but cooker and/or oven can be also fuelled by natural gas or butane.

The Table 2 summarizes the used hypotheses.

Table 2.Consumption per appliance penetration ratio and multi-equipment ratio of lighting and domestic appliance

	kWh/dw/y	% penetration ratio	multi-equipment ratio
lighting	340	100 %	-
natural gas cooker	575	63 %	1.00
butane cooker	575	14 %	1.00
ceramic cooker	400	14 %	1.00
induction cooker	400	8 %	1.00
fridge	650	100 %	1.00
freezer	500	6 %	1.00
washing machine	250	98 %	1.06
dishwasher	240	41 %	1.00
dryer	255	10 %	1.00
electric oven	100	92 %	1.81
gas oven	100	10 %	1.00
television	120	98 %	2.10
computer	91	37 %	1.74
other	22	100 %	2.50
stand-by	230	100 %	1.00

Consumption of electricity and fuels in Base Scenario

Using data of demand per dwelling according to the previous hypothesis and simulations and data of consumption per dwelling according to the information from the energy bills, a global energy balance is adjusted with the following equations.

$$C = \frac{D \cdot p \cdot m \cdot l}{\eta} \tag{1}$$

$$l = s \cdot ep \cdot t \tag{2}$$

Where C is the energy consumption; D is the energy demand; p is % of penetration of an energy use; m is multi-equipment ratio; l is % of energy demand supplied, η is the efficiency of equipment; s is % of total spaces simulated that are heated/cooled in real cases; t is % of total time simulated that heating/cooling is used in real cases and ep is the energy poverty index.

The main parameters that influence on the adjustment between consumption and demand are:

- Simulation results reported higher consumptions than the ones shown in the bills. The reason is the high penetration of electric heaters, used in only one room of dwelling, as well as a situation of low use of heating. The energy poverty can be assessed as a 9 % of houses in Spain according to references (Tirado, López, & Martín, 2012). Values used for s vary from 50 % to 90 % and for t, vary from 80 % to 100 %.
- Equipment's efficiency.

According to the survey analysis, the penetration of the different kind of equipment of heating and cooling is shown in Figure 3 and Figure 4. Both figures represent the distribution of different combination of heating/cooling equipment that is present in the whole residential block.

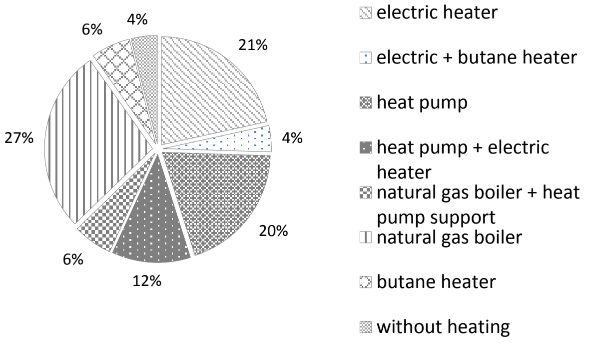
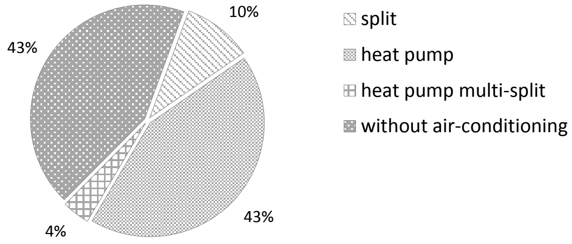


Figure 3. Type of heating equipment



The total results of energy consumption per dwelling are summarized in Table 3.

Table 3. Total consumption in the multi-family block per dwelling (kWh/dw/y)

	electricity	natural gas	butane	TOTAL
Lighting	340	0	0	340
Domestic app.	1 821	10	0	1 830
Cooking	86	361	81	527
Heating	607	914	126	1 647
Air-conditioning	61	0	0	61
DHW	0	1 234	168	1 402
TOTAL	**2 915**	**2 518**	**375**	**5 808**

Improvement of building envelope. Simulation results of heating and cooling demand

Three different retrofitting scenarios have been considered, by following energy efficiency criteria, economic balance and solutions feasibility.

Scenario 1 consists on a set of actions on the envelope as usually done in residential retrofitting in Catalonia. The objectives are to increase the degree of insulation of the main facades, roofs and windows, as the current values are clearly insufficient, and far from the latest Spanish Building Code requirements.

The actions introduced are as follows:

- External thermal insulation composite system (ETICS), giving the wall a thermal transmittance of about 0.50 W/m^{2}K (values vary depending on existent wall performance, which were always more than 1.2 W/m^{2}K). An external insulation solution allows minimizing thermal bridges, and to keep walls' thermal mass inside the house, which is an important passive cooling strategy for Mediterranean climates. As it has to be installed from outside the building, it also permits to perform a less invasive intervention for inhabitants.
- New windows with lower thermal transmittance (from an existent U-value of about 5.7 W/m^{2}K to 2.4 W/m^{2}K).
- External insulation layer with a gravel finish on roofs. This gives the roof a U-value of 0.30 W/m^{2}K, while the gravel finish keeps the roof protected from solar incidence on summer.

In scenario 2 the same solutions from scenario 1 are applied, and an intervention on solar protections is considered. External solar shadings are specified fulfilling these criteria:

- Complete practicability: an appropriate use permits to maintain winter solar gains.
- Air permeability: while shading is used, a correct rooms' ventilation is still possible.
- 70% obstruction: they permit sufficient natural light levels while used.

The actions taken in scenario 3 are as follows:

- Application of a 4 cm thick insulating mortar on the external side of walls. This solution gives the wall a higher thermal transmittance (U=0.83 W/m^{2}K) than ETICS system, but the solution is cheaper .
- New windows as in scenario 1.
- Roof external insulation as in scenario 1.
- External shading devices as in scenario 2.

The results observed in Figure 5 and Figure 6 are the following:

- A higher insulation level represents a great improvement on heating demand (from a 29% to a 63%), due to the poor initial conditions. It also gives an improvement on cooling demand.
- Dwellings under roof present higher improvements, as they have higher external surfaces proportion.
- Significant improvement in cooling demand is always due to external shadings, though effectiveness can vary from one case to another, depending on glass proportion on walls.
- Scenario 3 performs heating demands just a little higher than in other scenarios. It also represents a cooling demand slightly higher than in scenario 2. However as insulating mortar is a significantly cheaper solution, scenario 3 is the one chosen as the most appropriate.

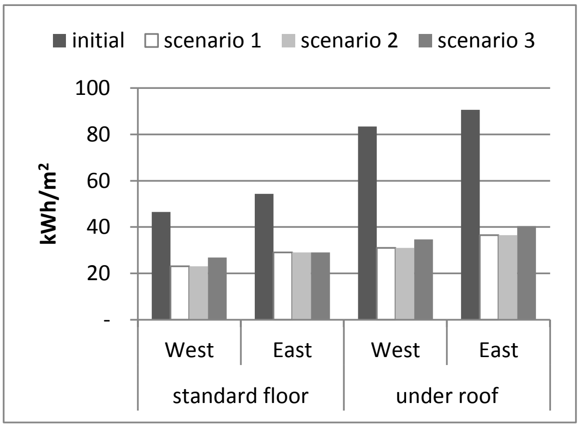


Figure 5. Yearly heating demands

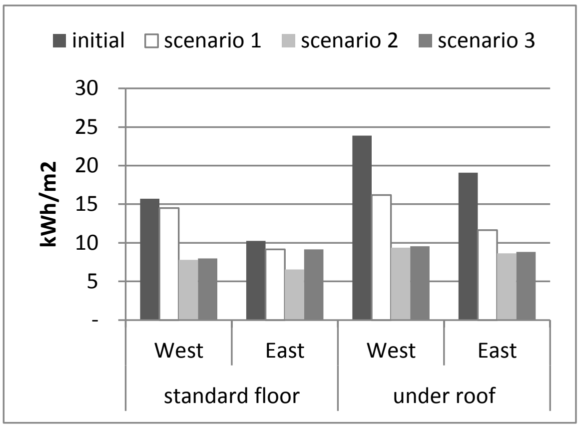


Figure 6. Yearly cooling demands

Table 4.Global yearly demands of Scenario 3

	kWh/y	Average kWh/dw/y	Average kWh/m^2/y
Heating	920 839	1 724	30.02
Cooling	245 220	459	7.99

Energy efficient systems and renewables

After application of measures in the buildings envelope to minimize the demand, some actions are proposed on the installations to improve efficiency and to introduce the renewable energies. All the cases are based on the selected Scenario 3b. The selected systems are detailed below:

- Scenario 3-FV. It consists on place PV panels (150 W/m^2; azimuth 0º; inclination 30º) on the area of the roof without shadings. The available surface is of 1 840 m^2 (276 kWp capacity). The annual production is calculated with (European Commission. IET-Joint Research Centre). It results of 333 935 kWh/y and coverage of 21% of total electricity consumption of Baseline Scenario.
- Scenario 3-CAL-I. The proposal states to replace the existing boilers for condensation boilers of high efficiency. The seasonal performance improvement is from 67% to 83%. The measure is considered to be implemented in 80% of dwellings.
- Scenario 3-CAL+ST-I. This measure adds to the previous one the introduction of solar thermal collectors to supply 63% of the demand of DHW. Each system is placed per building. The annual production of solar DHW is of 323 381 kWh/y. This was calculated with TRANSOL software (CSTB-AIGUASOL, 2011) using typical DHW load profiles for Spain. This solution will require constructing a technical room on the roof of each suitable building of around 20 m^2.
- Scenario 3-CAL+ST-C. This measure is based on 4 centralised systems of solar thermal collectors to supply 63% of the demand of DHW. With 4 systems of 220 m^2 each one (total 880 m^2) a production of 323 381 kWh/y is obtained. Moreover, there are 4 centralized boilers (4 x 388 kW) to supply the DHW support and the heating service of 80 % of the buildings. There are 4 technical room on the ground stage of about 50 m^2 each one.
- Scenario 3-COG-C. It consist of 4 centrals on the ground stage of 50 m^2, as in previous case, with centralized boilers (4x 388 kW) and 4 micro-cogeneration systems of 25 kW$_t$ each one (total 100 kW$_t$ and 168 kW$_e$). The annual production of heat is estimated to be 486 650 kWh/y and of electricity is 811 083 kWh/y, considering flat operation based on demand of DHW and heating.
- Scenario 3-BC-C. It consists of 4 centrals as in previous case but with heat pumps (4 x 450 kW) as system to generate heating and cooling to the buildings.

The measure that affects the heating and cooling demand requires also the refurbishing or new implementation of dissipation system inside dwellings (water radiators for heating or air distribution system for cooling). Besides that, the centralized systems consider that hot and cold water will be distributed by pipes around the block as in usual practice of district heating (and cooling).

The results of end-use energy consumption, primary energy and green-house gases emissions for each Scenario are shown in, Table 5, Table 6, Table 7, respectively. Percentage of savings regarding base case are also shown.

Table 5.End-use Energy Consumption per dwelling

scenario	electricity	natural gas	butane
	kWh/dw/y	kWh/dw/y	kWh/dw/y
Base	2 915	2 518	375
3b	2 654	2 169	327
3-FV	2 029	2 169	327
3-CAL-I	2 654	1 979	230
3-CAL+ST-I	2 654	1 386	230
3-CAL+ST-C	2 362	2 229	177
3-CAL+COG-C	843	4 669	177
3-BC+ST-C	2 755	636	177

Table 6. Primary Energy Consumption per dwelling

scenario	primary energy	savings vsbase	% savings
	kWh/dw/y	kWh/dw/y	kWh/dw/y
Base	10 666	-	-
3b	9 565	1 101	10%
3-FV	7 939	2 727	26%
3-CAL-I	9 260	1 406	13%
3-CAL+ST-I	8 625	2 041	19%
3-CAL+ST-C	8 712	1 955	18%
3-CAL+COG-C	7 373	3 293	31%
3-BC+ST-C	8 028	2 638	25%

Table 7. CO_2 emissions per dwelling

Scenario	CO_2 emissions	savings vsbase	% savings
	kWh/dw/y	kWh/dw/y	kWh/dw/y
Base	2 497	-	-
3b	2 245	252	10%
3-FV	1 839	658	26%
3-CAL-I	2 183	314	13%
3-CAL+ST-I	2 061	435	17%
3-CAL+ST-C	2 031	466	19%
3-CAL+COG-C	1 543	954	38%
3-BC+ST-C	1 961	536	21%

Economic analysis

The investment of the Scenarios is calculated in base of market prices in Catalonia, mainly according to the database (ITEC, 2012), as it is shown in the first column of Table 8.

To calculate the economic feasibility of different cases it has been considered the additional cost associated to energy efficiency improvement, besides the traditional refurbishment. Taking it into account, the costs decrease significantly as can be seen in Table 8 in second column. Considering this hypothesis it is calculated the discounted pay-back (Short, Packey, & Holt, 1995). Other values required in the analysis are: the discount rate, 3% , the electricity and butane price inflation rate, 6%, the natural gas inflation rate, 5% and the lifetime analysis of 30 years.

Table 8. Investment and additional cost related with energy refurbishment.

Scenario	total investment	additional investment of energy refurb.	discounted pay-back
	€/dw	€/dw	y
3b	6 089	1 717	21
3-FV	7 639	3 268	17
3-CAL-I	8 003	2 428	22
3-CAL+ST-I	9 074	3 499	23
3-CAL+ST-C	14 019	8 445	35
3-CAL+COG-C	13 595	8 020	21
3-BC+ST-C	19 897	14 323	>> 50

The business models of ESCO will permit to treat the proposed project in a holistic way. The results provided are a first step to carry out a detailed financial plan, containing the added value of a detailed energy balance of the present situation and the simulated energy performance in future scenarios. The scale economy of refurbishing project in a multi-family block of 600 dwelling will permit to obtain attractive discounts in the energy prices as well as in the investment that will enhance the development of the project with a better economic feasibility than the obtained with the present economic assessment.

DISCUSSION AND RESULT ANALYSIS

The conclusion of the results shown in the previous tables is that the option that provides the highest reduction of green-house gases emissions, with a ratio close to the 40 % is the cogeneration system, with the envelope improvement of Scenario 3b. This is followed by the photovoltaic proposal and in the third case the centralized system with heat pumps. However, this third case presents the worst economic performance. It is due to the requirement of double the pipe network and the share of air-conditioning in total energy demand of only 1%, instead of the penetration of the equipment in 57% of dwellings.

Finally, looking at the lowest payback the selection should be the photovoltaic scenario, followed by the cogeneration, as well as the refurbishment only of the envelope. Therefore, adding the energy, economic and environmental results the best option is a refurbishment based on: 4 cm thick insulating mortar externally on the walls, with roof insulation, windows refurbishing and external shadings (scenario 3) and 4 centralized systems of micro-cogeneration and central boilers to provide the heating and DHW services, or a photovoltaic system covering the non-shading places on the roof.

CONCLUSION

There are several identified barriers for Energy Service Companies to tackle refurbishment projects in the residential sector and the Mediterranean area. One of them is related to the low-energy consumption level which makes the economic numbers not very attractive for that type of companies. Other important barrier is the uncertainty associated to the energy demand / end-use energy consumption in the residential sector due to the variability in occupants habits, ownership of energy equipment and type and level conservation of dwellings. Few numbers and studies are available that give solid numbers to define common public-private partnership strategies to overcome this barriers in the Mediterranean area.

The present study starts from the idea that investments at block level in high dense areas can be a solution to overcome the identified barriers. The methodology that has been applied is a refinement of some past methodology applied at city level in Barcelona, which have been extended with detailed surveys in the field and more detailed building simulation. This has been proved to be very useful to characterize the energy consumption and the level of equipment giving a solid basis to analyse different retrofitting passive solutions and use of high energy efficient systems and integration of renewable energy sources. This study present detailed numbers to estimate the end-use energy consumption and results of several potential integral retrofitting actions.

Although pay-back results could be right for private owners, it could be hardly affordable for ESCO companies. Then, more research is needed to find suitable strategies than make refurbishment projects in residential sector attractive for ESCOs. Limitations of the study do not have been allowed to make a deep analysis of cost reduction of investments derived from intervention at block level. First estimations give a potential reduction of investment costs of 25% over the numbers presented in this paper, although this figure need to be checked with local companies.

NOMENCLATURE

C = energy consumption of electricity and fuels; corresponds to the energy provided to the dwelling by the utilities or from renewable sources, also named "final energy"

D= energy demand at the final use; also named "useful energy"

ep = energy poverty is the level of dwellings that do not reach minimum confort conditions

l= percentatge of energy demand that is covered with a certain energy system

m= multi-equipment ratio or average number of appliances per dwelling

η= efficiency of energy equipment

p = percentage of penetration of an energy use or type of equipment or appliance over the total dwellings

DHW = domestic hot water

dw = dwelling

kWh = kilowatt per hour

kW$_t$ = thermal kilowatt

kW$_e$ = electric kilowatt

PV = photovoltaic solar energy

s = percentatge of the total spaces considered in heating and cooling simulation that are supplied with energy system in real case.

t = percentatge of the total time of heating and cooling operation considered on simulations that real systems are operating.

y = year

U = thermal transmittance of a wall

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