# **Environmental Retrofit:** Energy upgrades of urban dwellings

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ABSTRACT: This paper focuses on retrofitting measures as vehicle to reduce heating energy consumption in the domestic sector. It reports on the potential energy savings yielded by common upgrading strategies in relation to the original constructive systems and building typologies. The investigation starts from a thorough study of the context which comprises the climate analysis, urban environment and constructive typologies. The basic thermal principles of each retrofitting technique are then explored to find out the patterns which allow the attainment of their optimum output in every situation. These patterns are confirmed by computer simulations which state different efficiency depending on the typology of the building subjected. The research provides also an estimation of the embodied energy of every system as further indicators on how to optimize resources in an energy retrofitting project. Keywords: retrofit, savings, techniques, typologies

#### **INTRODUCTION**

Energy consumption of buildings increases with age due to the deterioration of its elements. Therefore maintenance labours are systematically required to upgrade them and to extend their operational life. Using these works to improve energy efficiency would allow reducing fuel demand from the building sector, which is one of the highest consumers nowadays. In countries such as United Kingdom or Germany, it counts up to 50% of the total energy demand of the country. Looking into the building sector, housing is showed as the largest consumer group. This paper will focus on retrofitting measures as vehicle to reduce heating energy consumption in urban housing. A successful retrofitting is based on the previous analysis of thermal properties of materials, building elements, and constructive systems. The amount of energy saved will differ and the use of inadequate systems would result in costly works and material waste. For this reason, this paper brings some light upon potential savings and efficient retrofit measures in relation to the constructive context. The objective is to provide a work methodology for the preliminary stage of renovation projects which allowed knowledgeable decisions and the selection of the most convenient strategies in every case.

In last decades, research about energy conservation had been mainly addressed to new buildings. Nonetheless, relying energy policies only upon new developments will not deliver substantial benefits in the short term. Extending retrofitting measures to a global context is the most efficient way to reduce energy consumption from the modern city. There is however a need for further research to know how the building reacts to the implementation of an upgrading measure according to the properties of the constructive systems. The objective is to maximize the, getting the most from a given budget. This research has been contextualized in the Northwest of Spain, although its outcomes have a general application.

## THE CONTEXT

Galicia is a coastal region located in the Northwest of Spain, within the range 41°48' to 43°47'N and 6°44' to 9°16' W. The climate of this area is characterized by cool summers and mild winters and it is strongly marked by the proximity to the ocean, which acts as thermal buffer and humidity source. January is the coldest month with an average temperature of 8.85°C and August is the warmest one reaching a mean value of 19.85°C. Relative humidity is quite even with constant values around 72%.

Diurnal average values for are plotted in figure 1 which shows the smooth fluctuation of monthly temperatures and mild weather conditions throughout the year. When the comfort zone is overlaid, it can be noticed how external temperature is consistently cooler than neutral; therefore only a poor design could create overheating problems. In contrast, heating is required from November to March. As a result, energy conservation measures will need to focus in passive heating systems and heat losses control. However, a free-running performance is a feasible goal to achieve during great part of the year.



Figure 1: Monthly diurnal values for A Coruña (climate C1). Data from Ministry of Industry

In Galicia, as in the rest of European states, building sector is one of the three major factors in energy consumption, together with industry and transport. It counts up to twenty-seven percent of the total. Looking specifically into the building sector, the main division is made between domestic and service buildings. The former reached 17% of the total energy consumed in Galicia in 2005 and the latter added another 10%

By its end use in domestic sector, space heating is the first function of the energy consumed by European residential buildings (fig. 2). In Galicia, up to 50% of the total demand is for heating purposes. It illustrates the importance of architectural design in energy conservation. Many of the elements which determines heat load can be optimized by the architect during the design process to improve the environmental behaviour of the building.



Figure 2: Energy breakdown in Galician dwellings. Data from INEGA 2005[1]

The average delivered energy consumption in Galician dwellings is 120kWh/m<sup>2</sup> per year and the heat load is about 60kWh/m<sup>2</sup>year. These values vary accordingly to the age of the buildings, so that dwellings within vernacular buildings demand a heat load around 100kWh/m<sup>2</sup>year and those which have been built within the last decades demand an average of 40kWh/m<sup>2</sup>year.



Figure 3: Average annual heat load in relation to the building typology

## **BUILDING TYPOLOGIES**

In the last century architecture has evolved from a selective mode towards an exclusive mode [2]. While vernacular buildings showed a closer interaction with the external environment the constructive systems from the late 20<sup>th</sup> century tended to rely on insulation and mechanical services. At the same time that buildings became more insulated they also became isolated from outdoors benefits. The comparison of the thermal behaviour of the sole envelope without internal gains between a post-war and a contemporary building illustrates higher internal temperatures in the former despite having poorer materials. In this case both buildings benefit from solar accessibility but the highly insulated walls of the newer one diminish the reaction of internal spaces to get beneficial aspects from external conditions (fig. 4). When the internal gains are also considered (fig.5) an improved performance in the contemporary typology is illustrated. In older buildings, heat losses through the envelope are higher and when external temperature drops the internal follows, despite the action of internal gains. If the wall is well insulated, the building become less sensitive to the external conditions and the heat gains are higher than the losses, therefore the internal temperature will increase gradually.

This different performance suggests that renovation techniques applied on each building typology should respond to the specific properties of the original constructive systems.



-External Temperature (deg.C) - Dry Bulb (deg.C) -

Figure 4: Envelope's thermal behaviour of two typologies



*Figure 5: Free running performance of two typologies* 

#### **ENVIRONMENTAL RETROFIT**

Many research programs carried out in Europe during last decade focussed on potential savings in heating energy consumption after retrofitting projects (table 1). They considered the implementation of single or combined measures in order to predict their effectiveness in the future. The broad range of results achieved by these investigations demonstrated that predictions based only on retrofit techniques can be imprecise. If every single variable is taken into account, the number of hypothetical scenarios becomes too vast to be handled. In this research determining variables are defined by building typologies and retrofitting techniques are analyzed in relation to the constructive system where they are applied.

Table1: Summary of savings potential from retrofit solution according to several studies [3, 4, 5, 6, 7, 8, 9, 10]

			Envelope Insulation			Windows
			Wall	Floor	Roof	Replacement
Dalenback, J.	1995	70%	Yes	No	No	No
Balaras, C.A. et al	2000		20-40%			20%
	2000		24-28%	18-20%	5-6%	5-12%
Bell, M. & R. Lowe	2000		30%	No	5%	7%
Ponêek, J.et al	2004	46%	Yes	Yes	No	Yes
Hong, S.H. et al	2006		10-17%	No	No	No
Richarz, et al	2006		30-40%	9%	9-12%	5%
	2006	30-47%	Yes	Yes	Yes	Yes
Donkelaar, M.	2007	30-60%	Yes	Yes	Yes	Yes
Cerdá Institute	2008		5-16%	No	4-14%	3-10%

#### **INSULATION**

Thermal insulation is intended to control and reduce the heat flow through the envelope of the building. Heat flow can be reflected by a bright or shiny surface (reflective or radiant [11] insulation) it can be diminished by air cavities and high thermal resistance materials (resistive insulation) or it can be altered in its timing (capacitive insulation) [12]. The most common system in a mild climate is resistive insulation by using plastic polymers such as polystyrene or polyurethane. It is a relatively easy and cheap solution in old buildings which lack of a proper envelope. Buildings before the thermal code of 1979 used to have a high conductance and many of them still remain in the market. For that reason the addition of an insulation layer is often offered as the first alternative when a retrofit project is undertaken. There are two main aspects to consider when adding an insulating material to an existing building: the thickness of the position. Relation between insulation thickness and heat load reductions are not proportional. It means that beyond a certain point, further insulation will not deliver higher energy savings. Furthermore, many insulation materials are harmful for the environment. Then, using them in the right proportion will avoid unnecessary over-insulation and misuse of environmentally sensitive material.

The position of the insulation layer has an important influence in heat flow patterns due to the different dynamic properties of materials. Many historic buildings were made using thick masonry walls and due to the high thermal capacity of the stone the heat flow is slowed down. In this way, temperature fluctuations are softened and internal conditions are stabilized. When the insulation layer is added, the performance of the wall changes and depending on its position the benefits from thermal inertia can be highlighted or distorted. Figure 6 shows the effect of insulation on a masonry wall in a vernacular building. The original wall presents a smooth behaviour, keeping internal temperature constantly between 12.5°C and 15°C and a delay of 5 hours respect to external temperature peaks. Maximum external value of 13.6°C is reached the first day at 16p.m. while maximum internal surface temperature for the same day is 14.08°C at 21p.m. Adding an external insulation layer results in a more even internal temperature, keeping the same time lag and increasing the average values. If the insulation is placed internally the average temperature is close to that achieved by external insulation, but the balancing effect of the thermal inertia is reduced. The resultant surface temperature shows higher fluctuations and faster reactions to external thermal variations (time lag reduced to 3hours). Dwellings have a continuous occupancy pattern and therefore keeping a constant temperature is desirable. A quicker reaction to heating inputs would be more suitable for offices or schools where the occupancy is occasional and they remain empty when the lowest external temperatures occur.

Walls are the largest element of the building's envelope and therefore an insufficient insulation on them is one of the main causes of heat losses. However, attention must be also addressed to the horizontal elements of the building: roof and floors. The roof is one of the most environmentally sensitive features in buildings; they are constantly exposed to weather conditions, receiving rainwater, wind pressure and solar radiation. The floor slabs are more protected but they produce heat losses towards the unoccupied spaces, either the ground or a basement. The joint between the slab and façade is other highly sensitive element which can produce thermal bridges on its perimeter.



*Figure 6:* Effect of insulation on the surface temperature of a masonry wall

#### WINDOWS

Windows are the weakest element of the building's envelope. The high transmittance of the glazed area and the air leakage through the joints are an important cause of heat losses. On the other hand they counteract part of those losses by introducing solar gains into the building.

Upgrading measures in windows will tend to improve their thermal resistance and airtightness with a special care to the solar properties of the glass. The difference between materials requires taking into consideration the combined performance of frame and pane. Big differences between their conductivities could result on a thermal bridge in the meeting point, thus diminishing the benefits from the upgraded elements.

When windows are replaced, the main factors to consider are air permeability and thermal conductance. Fresh air requirements usually oblige to ensure a minimum infiltration rate. Therefore thermal behaviour will be the determinant factor to select the new window Figure 7 illustrates a comparison among three typical glazing systems to determine the relationship between gains and losses. Calculations were performed to obtain the average daily net gains or net losses per square meter of a glazed southern surface for the coldest month of the year under Galicia climate conditions. It can be noticed that any of the windows succeed in achieving a positive balance. The low emissivity window is the closest one to the neutral line but there is a small difference with the simpler double glazed window, which is, on the other hand, much more economic. From this graph it can be also noticed that a window with a U-value above 4 W/m<sup>2</sup>C will be a likely heat loss source during the cold period. Therefore any renovation project which increases windows size should adopt corrective measure to avoid higher heat loss rate.



*Figure 7:* Comparison of the thermal behaviour of three window systems without night insulation shutters

## SOLAR CONCEPTS

The implementation of solar concepts in renovation schemes beyond the use of direct gains from windows has as main drawback their impact in the external appearance of the building; the architectural language can be completely distorted. Glazed galleries and solar walls are the most common applications of solar concepts in renovation. However, the main disadvantage of these systems is on the timing since the highest input of solar gains may occur when it is not really needed. Through series of parametric studies it is possible to decouple the useful from the total solar gains.

## ENERGY SAVINGS

The analysis of energy savings starts from the definition of four models regarding building typologies. Awareness of differential factors and the understanding of architectural elements lead to the identification of their influence on each retrofit strategy. The objective is to find an interaction pattern between the existing building and the upgrading options, regarding not only their global energy efficiency but also the economic feasibility.



Figure 8: Individual energy savings and embodied energy of retrofitting measures

Figure 8 assess individual retrofitting strategies. Wall insulation is verified as the most efficient measure in old buildings. If the building had already been insulated, as it is the case of the eighties' typology, the impact of the retrofit is minimal and when the embodied energy required for the task is taken into consideration, it points out that there is bigger waste during the process than the energy saved during the life cycle after the renovation. In contrast, the effect of insulation on older buildings is showed as highly effective, reaching potential savings up to 49% in the best case. A direct relationship between the age of the building and the effectiveness of insulation is stated throughout the simulations. Regarding the elements to be upgraded, external wall is stated as the first priority since it consistently shows the highest saving potentials. The choice of thickness and position should be evaluated bearing on mind the relative cost and the embodied energy wasted. Insulation of horizontal elements deliver less overall savings since the upgraded surface is normally smaller. However they are often essential to provide comfort in adjacent dwellings. Windows upgrading is postulated as one of the most effective strategies, not only by improving thermal resistance but also by reducing infiltration. Energy savings related to solar walls highlight the influence of the thermal conductivity of the original facade which is

behind the glass. When there is a combination of solar availability and poor façade savings can reach 52% with transparent insulating materials.



Figure 9: Combined energy savings and embodied energy of retrofitting measures

Case 1.2: 50mm external wall insulation Case 2.2: 100mm roof insulation Case 3: 100mm ground floor insulation Case 4.2: Windows replacement Case 5.2 Solar wall Case 6: Glazed gallery

combined action Figure 10 illustrates of complementary retrofit solutions in the different building typologies, together with their embodied energy. Bar charts on the left represent the final annual heat load once the retrofit was implemented in kWh/m<sup>2</sup> of heated floor area; it also states the percentage saving in relation to the original state. The right column indicates the total embodied energy of every measure in kWh/m<sup>2</sup> of heated area. In practise, retrofit measures are seldom applied individually and the usual strategy is to upgrade two or more elements at the same time. The combined effect of the upgrades can enhance the single benefits of each one. That happens when the strategies are complementary of each other. In other cases, the actions are redundant and the delivered benefits are lower than expected from the individual performance. The improvement of the insulation is stated as the most effective measure in almost every case. But it has a low energy impact if the building had already built using insulation materials. In these cases it is recommended to schedule a maintenance plans rather than retrofitting labours. Insulation of roofs and lowermost levels though globally energy inefficient is sometimes necessary for comfort reasons, therefore the optimization of the material would be in these cases especially commendable. Windows upgrading is the system which shows a more homogeneous performance in all models, despite its high cost, it delivers high savings and reasonable payback periods which could promote its implementation. It is also worth to mention the existing scope for the use of solar walls in the oldest buildings. In post-war developments it could not only be a means to improve energy efficiency but also to upgrade the image of the buildings. This typology is also stated as the best subject of glazed balconies additions, which have the added value of providing a further space to the dwelling.



Figure 11: Relation between retrofit measures and heat load

Energy consumption in retrofitted dwellings are rationalized in figure 11. Typologies are illustrated by the coloured lines and retrofit techniques by the letters. The horizontal axis represents the heat loss ratio of the building. When an upgrading measure is applied this value is normally reduced. The first three steps of the combined analysis (cases A, B and C) mainly acted on that way, improving the envelope's thermal resistance and reducing heat losses. The darkest central patch in the graph represents the area where most cases would be located according to simulations. Then they can be affected by external factors either increasing energy consumption (i.e. overshadowing, northern orientation) or reducing it (i.e. good solar availability, airtightness). They lighter grey areas represent this margin of variation.

## CONCLUSION

This research has pointed out that effort has to be focussed on the existing building stock rather than in promotion of new sustainable developments. The main body of this paper has consisted on a study of the meaning and the effect of retrofitting interventions on the different building typologies. A hierarchy of priorities was found out for each type of building regarding the balance among energy savings and embodied energy. In this way, the addition of insulation layers has been stated as highly effective for older buildings with poor envelopes. In contrast, a combination of different measures results more convenient for newer constructions. Results came to confirm the findings from literature research and precedent studies. There is however an intention in this paper to highlight the different potential of upgrading measures depending on the previous state of the building. It is not possible to generalize saving potentials from singular measures to all the building stock unless there is a previous knowledge retrofitting principles and a clear building classification. This is important if general policies are to be implemented, so that different actions can be prioritized to optimize resources.

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