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Cost optimal analysis for energy renovation of old buildings in northern Italy

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Summary

Abstract

The European commitment to becoming carbon neutral by 2050, includes a huge effort to reduce the energy consumption of the European building stock, that is responsible for 36% of total CO_2 emissions.

The package of rules for buildings, called EPBD (energy performance of buildings directive), contains the guidelines to lead member states into this ecological transition.

EPBD instructions not only set strong consumption limits for new buildings but also push for a refurbishment of the worst and highest energy consuming houses, that generally are also the oldest house.

This thesis has the purpose of finding the best solution to renovate old buildings sited in northern Italy. To do so one real old building, erected in the 19th century, is used as case-study.

To find the best solution vary scenarios are simulated and then it is applied the cost optimal analysis that allows to find the best balance between the initial investment and the subsequent energy savings.

The first part of the thesis contains an introduction to the European and Italian legal context and it summarizes the rules over the construction and refurbishment of buildings; in this way all the subsequent work can follow the rules and all the simulated scenarios respect the legal parameters.

In the second part of the thesis, I created a model of the case-study building and I calculated its current thermal need with EdilClima software, then I simulated various thermal insulation scenarios and calculated the new thermal needs. After that, I simulated the heating and cooling plant and the renewable generation to choose between solar thermal or photovoltaic and to find the best power size.

In the third and last part of the thesis, I performed the economic analysis, calculating the initial investment of the various elements simulated in the technical part, such as the thermal insulation and the radiant floor.

After that, following the European Commission’s guidelines, I made the cost optimal analysis to find the best case among all the cases simulated. And the results of that analysis also allows to discover which technologies pay off their installation cost or not.

European housing stock and energy certificates

Overview and EU commitment

The climate change and the struggle for reducing CO_2 emissions are the topic of the decade. This thesis focuses on the household and building sector and its huge environmental impact, in fact, it is responsible for the 36% of the CO_2 emissions and it consumes the 40% of the total final energy for heating and cooling purposes[1]. That means that in 2022 it caused the emission of around 1 billion metric tons of carbon dioxide ($GtCO_2$)[2].

The European Commission has been working to fight the climate crisis for years and one of the latest project is “Fit for 55” to meet a minimum 55% EU reduction in greenhouse gas (GHG) emissions by 2030. Inside this package of rules there is the EPBD (Energy Performance of Buildings Directive) with the aim to make the new and already existing buildings more energy efficient[3].

EPBD and Energy Classification

In December 2021, the European Commission proposed a revision to the Energy Performance of Buildings Directive (EPBD) and the new set of rules considers the progress of the technology and the economic feasibility to design new environmental goals. These goals are listed below by their deadline date[4]:

- 2026 obligation to all new buildings occupied, operated or owned by public authorities, to be zero-emission.
- 2027 obligation to all non-residential and public buildings to reach EPC class E.
- 2028 buildings should be equipped with solar technologies if and where feasible.
- 2028 obligation to all new residential buildings to be zero-emission.
- 2030 obligation to all residential buildings to reach EPC class E.
- 2030 obligation to all non-residential and public buildings to reach EPC class D.
- 2033 obligation to all residential buildings to reach EPC class D.
- 2035 fossil fuels in heating systems have been totally phased out, if and where feasible.

To fully understand the directive, it is necessary to examinate two key-terms that are “EPC class” and “zero emission building”.

EPC Classification and the Italian APE

Energy Performance Certification EPC is not yet a regulated standard among all the members states, rather it represents a generic certificate about the energy class of the building that is mandatory for every EU state. In the most recent review of the EPBD, one of the purposes is, in fact, to ensure more harmonized standards across Member States and to set a minimum energy performance standard. This new proposal is completing the legislative process so, while writing this document, is not operative.

Since there is not a unique methodology to evaluate the performance of the building and the analysis of this work is on a building in Italy, the discussed method is the Italian one.

Attestato prestazione energetica APE

The Italian certification for the energy performance building, named “Attestato prestazione energetica APE” got legal value in 2015 with the inter ministry decree “*Decreto interministeriale 26 giugno 2015 - Adeguamento linee guida nazionali per la certificazione energetica degli edifici*”[5] and it was coupled with the decree “*Decreto interministeriale 26 giugno 2015 - Applicazione delle metodologie di calcolo delle prestazioni energetiche e definizione delle prescrizioni e dei requisiti minimi degli edifici*”[6], to create the guidelines about the energy requirements for buildings.

The requirements for the buildings change on the base of the work done so the categories are the following:

- New building.
- First level of important renovation, the renovation covers more than 50% of the external surface walls and it is installed a new heating or conditioning plant.
- Second level of important renovation, the renovation covers more than 25% of the external surface walls.
- Energy requalification, the renovation covers less than 25% of the external surface walls or it is and it is installed a new heating or conditioning plant.

There is also a further division based on the climate region[7]:

- Region A: area with heating degree-day under 600

- Region B: area with heating degree-day between 600 and 900
- Region C: area with heating degree-day between 900 and 1400
- Region D: area with heating degree-day between 1400 and 2100
- Region E: area with heating degree-day between 2100 and 3000
- Region F: area with heating degree-day over 3000

A heating degree day (HDD) is a measurement designed to quantify the demand for energy needed to heat a building. It is calculated as the sum of only the positive difference between the indoor temperature (20°C) and the average temperature of the day, over the period of time when the heating system is working (winter).

For a new building or the first level important renovation the requirements set are listed below.

Region	Value 1	Value 2	Value 3	Value 4	Value 5
A, B	0.43	0.35	0.44	3.0	0.8
C	0.34	0.33	0.28	2.2	0.8
D	0.29	0.26	0.29	1.8	0.8
E	0.26	0.22	0.26	1.4	0.8
F	0.24	0.20	0.24	1.1	0.8

Table 1. Legal minimum transmittance value in case of first level renovation.

All the values are expressed in W/m^2K.

Where:

Value 1 stands for the thermal transmittance U of vertical opaque structures, to the outdoors, to non air-conditioned or against the ground.
Value 2 stands for the thermal transmittance U of horizontal or inclined opaque roof structures, to the outside and non-air-conditioned rooms.
Values 3 stands for the thermal transmittance U of horizontal opaque floor structures, to the outside, unconditioned rooms or against the ground.
Values 4 stands for the thermal transmittance U of transparent and opaque technical closures and shutter boxes, including window frames, to the outside and to non-air-conditioned rooms.
Values 5 stands for the thermal transmittance U of vertical and horizontal opaque structures separating neighboring buildings or building units.

The same table for second level important renovation and energy requalification has different values.

Region	Value 1	Value 2	Value 3	Value 4
A, B	0.40	0.32	0.42	3.0
C	0.36	0.32	0.38	2.0
D	0.32	0.26	0.32	1.8
E	0.28	0.24	0.29	1.4
F	0.26	0.22	0.28	1.0

Table 2. Legal minimum transmittance value in case of second level renovation

Moreover, in the case of new buildings or first level renovation, at the comma 5 of the paragraph 3.3 of the same decree requires that the thermal transmittance of the walls between two residential units or of the walls that separate the outside from non-heated rooms must be below 0.8 W/m^2K. It must be clear that if the wall is not touched by the renovation work, it doesn't have to follow the prescription.

Other parameters are defined and must respect some minimum or maximum values. In example, the medium heat exchange coefficient H'_T [W/m^2K] must respect the following:

Shape ratio S/V	Climate Region				
	A,B	C	D	E	F
S/V >0.7	0.58	0.55	0.53	0.50	0.48
0.4< S/V < 0.7	0.63	0.60	0.58	0.55	0.53
S/V < 0.4	0.8	0.8	0.8	0.75	0.7

Table 3. Medium heat exchange coefficient H'T [W/m2K] prescribed by the law

Other less important parameters are defined but are not listed in this document.

The requirements reported above are strictly related to the energy performance classification, in fact the values for the new building are the same that identify a standard (ideal) building that is the reference for the classification. As written in the decree[6]: "the energy performance of buildings is determined on the basis of the amount of energy required annually to meet the needs associated with a standard use of the building and corresponds to the overall annual energy demand in primary energy for heating, cooling, ventilation, domestic hot water and, in the nonresidential sector, for lighting, elevator and escalator systems".

In the annex 1 of the "APE" decree[5], the limiting value of each energy class are defined:

	Classe A4	$\leq 0{,}40\ EP_{gl,nren,rif,standard\ (2019/21)}$
$0{,}40\ EP_{gl,nren,rif,standard\ (2019/21)} <$	**Classe A3**	$\leq 0{,}60\ EP_{gl,nren,rif,standard\ (2019/21)}$
$0{,}60\ EP_{gl,nren,rif,standard\ (2019/21)} <$	**Classe A2**	$\leq 0{,}80\ EP_{gl,nren,rif,standard\ (2019/21)}$
$0{,}80\ EP_{gl,nren,rif,standard\ (2019/21)} <$	**Classe A1**	$\leq 1{,}00\ EP_{gl,nren,rif,standard\ (2019/21)}$
$1{,}00\ EP_{gl,nren,rif,standard\ (2019/21)} <$	**Classe B**	$\leq 1{,}20\ EP_{gl,nren,rif,standard\ (2019/21)}$
$1{,}20\ EP_{gl,nren,rif,standard\ (2019/21)} <$	**Classe C**	$\leq 1{,}50\ EP_{gl,nren,rif,standard\ (2019/21)}$
$1{,}50\ EP_{gl,nren,rif,standard\ (2019/21)} <$	**Classe D**	$\leq 2{,}00\ EP_{gl,nren,rif,standard\ (2019/21)}$
$2{,}00\ EP_{gl,nren,rif,standard\ (2019/21)} <$	**Classe E**	$\leq 2{,}60\ EP_{gl,nren,rif,standard\ (2019/21)}$
$2{,}60\ EP_{gl,nren,rif,standard\ (2019/21)} <$	**Classe F**	$\leq 3{,}50\ EP_{gl,nren,rif,standard\ (2019/21)}$
	Classe G	$> 3{,}50\ EP_{gl,nren,rif,standard\ (2019/21)}$

Table 4. Conversion from primary energy consumption to the equivalent APE energy class.

Where the $EP_{gl,nren,rif,standard}$ is the global non-renewable Primary Energy calculated on the standard building mentioned in the previous paragraph. To calculate the primary energy associated with the energy vector used is available a table[6], here only the most important vectors are reported.

Energy vector	$f_{P,nren}$	$f_{P,ren}$	$f_{P,,TOT}$
Natural gas	1.05	0	1.05
Electricity from the grid	1.95	0.47	2.42
Electricity from renewable generation	0	1.00	1.00

Table 5. Primary energy associated to different energy vector.

The results of the APE calculation are shown to the public with the following graphic badge.

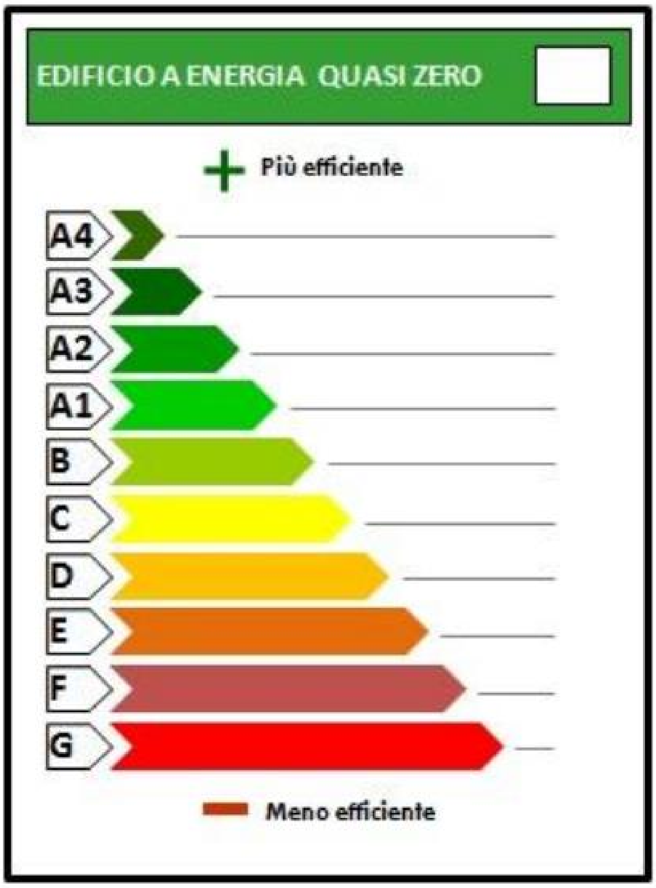


Figure 1. . Energy tag from the allegato 1 of the APE decree

Moreover, in 2021 the decree "DECRETO LEGISLATIVO 8 novembre 2021, n. 199"[8] was published and it requires that: new building or existing buildings undergoing an important renovation must cover simultaneously the 60% of the need for heating, the 60% for cooling and the 60% for domestic hot water, by renewable energy production. Also, the same decree prescribe the minimum power for the renewable energy generation plant as 0.05 kW for each square meter of ground surface occupied by the building in the case of new building and the half of that for renovated buildings.

Regional legislation

In Italy, regional legislation is overlapping on the one of the central state, this means that based on the region where the building is located, it must follow additional rules. The case studio of this work is built in Piedmont so some minimum requirements are different from the ones in the previous paragraphs.

The transmittance values to follow in Piedmont are reported below as written in "Piemonte DGR 49-11968"[9]:

Thermal transmittance of:	[W/m²K]	+30%
Opaque vertical structures	0.25	0.325
Opaque horizontal or inclined structures	0.23	0.30
Transparent closures (average glass/frame value)	1.7	Nan

Table 6. Minimum transmittance value as indicated by regional law.

In the table is present a column with the value increased by 30% because in the same decree at comma 1.3 is explained that for building under renovation, the value in the table can be increased by 30% for the opaque structure.

Between the regional set of rules and the central state rules, the project supervisor must always apply the strictest parameter.

Zero Emission Buildings

To date, European authorities have not yet established an unambiguous definition for zero-emission buildings; however, the underlying concept is clear and shared by the scientific community. The definition issued by The Norwegian Research Centre on Zero Emission Buildings is divided into 5 levels[10] and summarizes the various proposals to date, introducing at each level an additional criterion to be met:

1. ZEB – O: The building's renewable energy production compensate for greenhouse gas emissions from operation of the building.
2. The building's renewable energy production compensate for greenhouse gas emissions from operation of the building minus the energy use for equipment (plug loads).
3. The building's renewable energy production compensate for greenhouse gas emissions from operation and production of its building materials.
4. ZEB – COM: The building's renewable energy production compensate for greenhouse gas emissions from construction, operation and production of building materials.
5. ZEB – COMPLETE: The building's renewable energy production compensate for greenhouse gas emissions from the entire lifespan of the building. Building materials – construction – operation and demolition/recycling.

For comprehensiveness, other definitions are reported below but it will be clear that the concept is the same.

From the paper by Skaar and other published in 2018[11], it is possible to read:" A zero emission building is an energy-efficient building with on-site renewable energy generation that can export enough energy to compensate for the carbon footprint of the building's own energy and material consumption in a life-cycle perspective". Ruparathna in 2017[12] gave a similar definition:" Net zero emission buildings use emission-free energy and supply the energy demand through on-site renewable energy generation".

Therefore, in the life cycle of a building there are three main phases that emit Green House Gases (GHG): operation, construction and demolition; the last two are considered "embodied" because their contribute is enclosed in the building and not dependent on user consumption.

For the majority of buildings to date, the operational phase turns out to be the most energy-intensive and consequently the one with the greatest environmental impact. In contrast, for new buildings, designed with attention to energy conservation, the phases that emit the most CO_2 into the atmosphere are construction and demolition.

The zeroing of the emission caused by a building throughout its life cycle, is possible thanks to the "Net Zero Emission" mechanism[13], which associates with each unit of energy generated through renewable sources a reduction in CO_2 equal to the amount that would be emitted through generation with traditional sources. Therefore, as some experts point out[13], zeroing the impact of a building will become more complex the more decarbonized the grid (in the area where the building stands) will get, because the CO_2 saving per unit of renewable energy produced would be minimal.

In addition, when the building has insufficient capacity to produce renewable energy (for example, a building with poor solar exposure and a small PV-covered area), it is possible to create new renewable energy plants outside the boundary of the property on which the house stands, to undertake reforestation or CO_2 capture campaigns. Finally, certificates can be purchased for the CO_2 emitted and not offset by the above-mentioned interventions.

Net Zero Emission protocol is always accompanied by the Energy Efficiency First Principle (EE1st). As it is essential to reduce in absolute terms the energy consumed by a building to ensure an adequate level of comfort for those living inside.
The efficiency principle is necessary to avoid the possible but not conscientious case of a building with terrible thermal insulation but with a high PV generation and so still scoring with a top environmental class.

To give a better overview of the challenge, the JRC in its paper about ZEB[13], makes four different groups for the energy use and are textually reported below:

(1) Building related, regulated: heating, cooling, ventilation, DHW, lighting and auxiliary energy for pumps, control and automation:
(2) Building related, unregulated: energy consumed by lift, elevators, escalators, automatic doors, safety and security systems, communications systems and any other technical systems needed for the proper functionality of the building. Worldwide, elevators are responsible for 2% – 10% from the total energy consumption of a building whilst during peak hours the share could reach at 40% (Brown et al., 2012). Moreover, across the EU, in 2008, elevators and escalators accounted for a share of 0.7% in the total electricity consumption (De Almeida et al., 2012).
(3) Non-building-related, user-related: energy consumed by plug-in appliances (TV, refrigerators, IT equipment, etc.) and production related energy and any other energy use generated by the

building's user. On the other hand, this category generates heat gains, therefore having a positive contribution on the energy performance of buildings by decreasing the heating need. However, worldwide, the use of IT devices is associated with 3% electricity demand and 2% of the GHG emissions (Brown et al., 2012).

(4) Operational water use: includes all water used by building integrated water consuming processes such as: drinking water, water for sanitation, irrigation of green area integrated in the building, water used by the HVAC systems, pools, fountains and any other specific water use;

Finally, when considering the more stringent definition of building and zero emissions, for which GHG emissions must be offset for the entire life cycle of the building, the challenge becomes even more difficult[14,15] and its feasibility will depend on the cost of building materials generated with innovative processes that reduce emissions and research developments on new production technologies, in 2021 cement production caused the emission of 1.67 billion tons of CO2 globally[16].

The housing stock situation in Europe

After the description of the legislative context and its reason to be, in order to complete the analysis, it is necessary do an overview of the housing stock and the market.

It is estimated that there are 25 billion m2 of useful floor space in the EU27, Switzerland and Norway, divided in 75% residential and 25% non-residential. The report about the status of the housing stock in Europe, "Europe's buildings under the microscope"[17] redacted by BPIE (Building Performance Institute Europe) on data until 2011, claims that only between 14% and 19% of houses are built between 1990 and 2011. In general, a substantial share of the stock in Europe is older than 50 years with many buildings in use today that are hundreds of years old. More than 40% of the residential buildings have been constructed before the 1960s when energy building regulations were very limited. Most of the member states in the South have natural gas as first fuel, instead in the north the first fuel is oil while central and east countries prefer coal; this also mean a different level of GHG and pollutant emissions. Nevertheless, the consumption experiences two trends[18], an increase in the share of electricity and natural gas (+50%) and a decrease in solid fuels (-75%) and oil (-27%).

In terms of CO_2 emissions, buildings are responsible for around 36% in Europe. The average specific CO_2 emission in Europe is 54 $kgCO_2/m^2$, where the national values of $kgCO_2$ per floor space vary in the range from 5-120 $kgCO_2/m^2$.

Italy stands among the best countries with little more than 40 $kgCO_2/m^2$, the states from the eastern Europe are the worst with almost the double of the emissions, instead Norway is the excellence with only 10 $kgCO_2/m^2$.

With these data about emissions, the current estimations are that in Europe the 15% (at least)[19] of the 40 million buildings are in EPC G class and another 15% is rated F; this means at least 40 million buildings across the EU will have to be renovated by 2030.

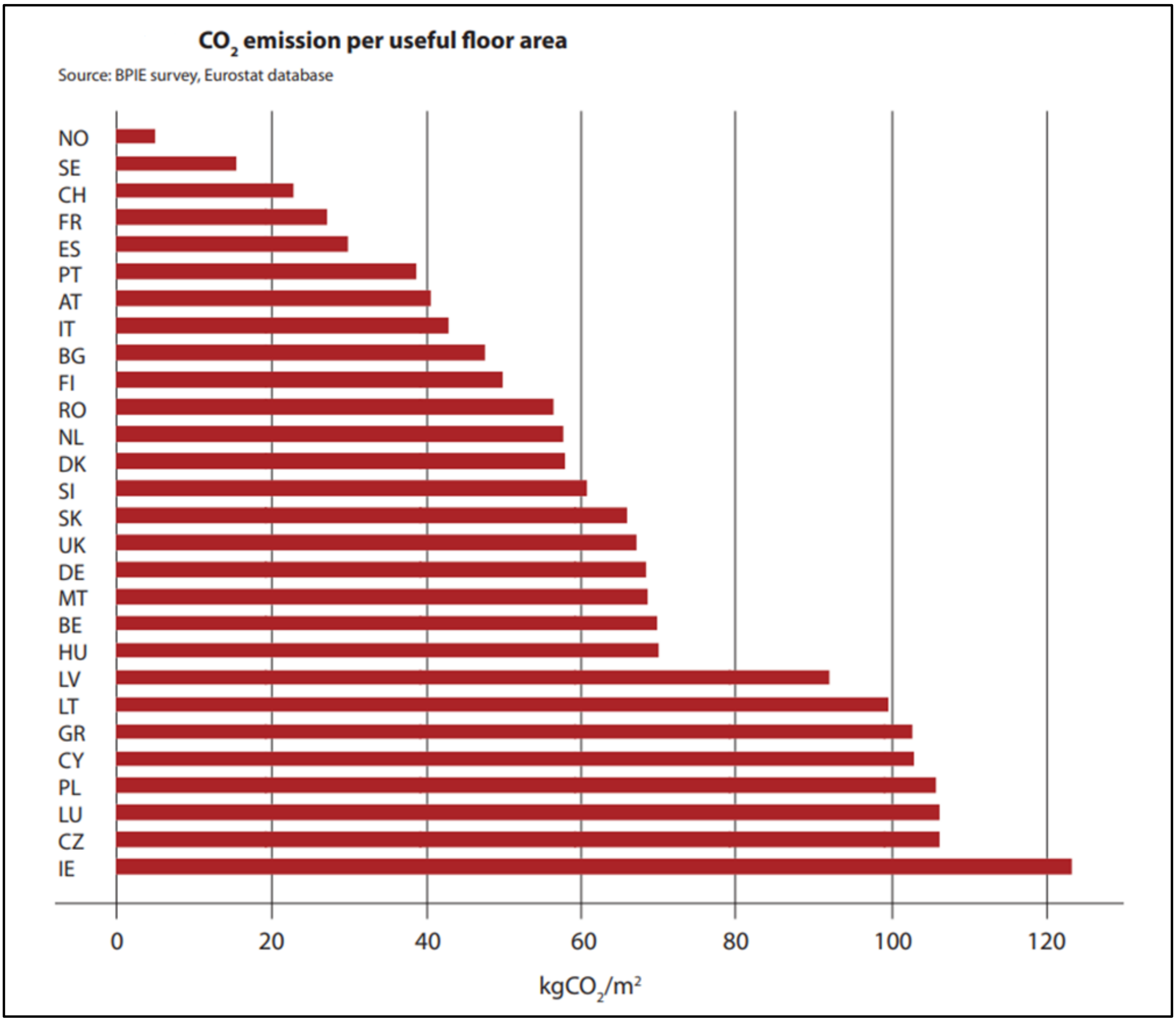


Figure 2. kgCO2 per floor space, image from BPIE survey

Closeup on Italy

Since in Europe, as seen above, every country has different policies, comfort standards and consumption habits it is necessary put under the spotlight the data of each single state, in this case Italy.

First raw estimation[20] is that there are14 million buildings and 35,7% of them are tagged as G class that means 4,5 million of buildings. The same calculation on real estate units shows that 13 million units are currently in the lowest energetic category.

The reason of a such high rate of G class buildings is due to the fact that in Italy buildings are really old: 40% are built before 1960, 53% between 1961 and 1990 and only 7% after 1990[17].

As shown in the following graph, the older the building and higher is energy consumed.

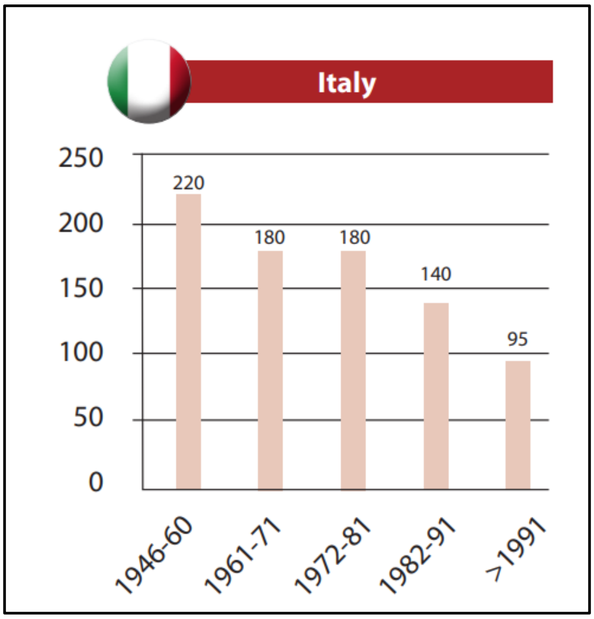


Figure 3. Average heating consumption levels in terms of final energy use (kwh/(m2a) of single family homes by construction year

The latest ENEA (Agenzia Nazionale Energia e Ambiente) report about building energy certification[21], shows a slightly better situation with only 30% of G class housing units but the overall situation is that 70% is the bad class (G,F and E). The positive data is the 4.7% of units classified as A4, thanks to the rules that impose high standards for new building.

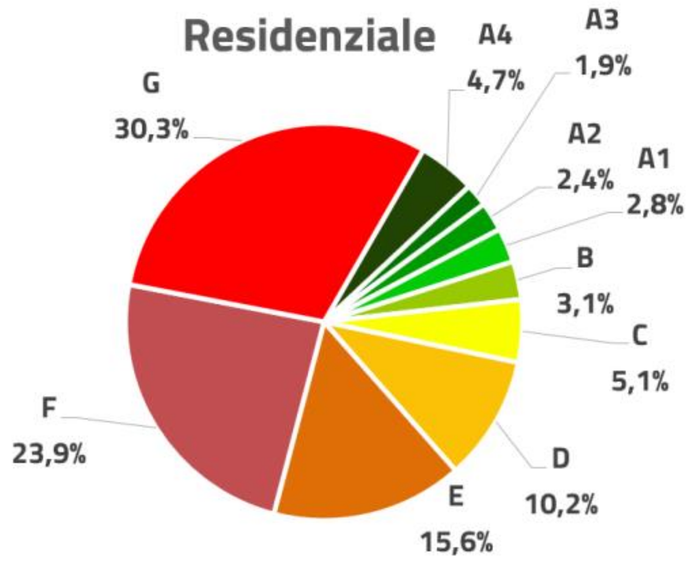


Figure 4. APE class situation in Italy. Source: ENEA

Energy need of an existing building

Renovation is more likely than building from zero

This thesis has the purpose to analyze an existing building in Italy to find the best scenario for economic return, the best one for energy saving, and the best for making it a zero emission building.

The choice of an existing old building is due to practical reason, in fact, as written in the previous chapter, the share of low performing housing units is 70% and more than the 30% is in the worst class (G class). There is also a low rate of new construction in Italy that means that chance is that a house owner will renovate its house instead buying a new one. This is also linked to the cost, because renovating will be, in most cases, cheaper than tearing down the old house to build the new one.

Moreover, renovating an old building has in itself a random level of difficulty: each house has its own features and it can be difficult to reach a good energy class with structural and legislative constrains: for example the house can have an insufficient height of the rooms or a bad window orientation.

This work will simulate various scenarios in order to check the best practices on an economic point of view and will evaluate the technologic and economic feasibility of making the old building into a ZEB.

The existing building description

The house chosen for this study it is really representative of the Italian housing stock: it was built in the end of the 19th century, then it was partially renovated after the WWII and then discontinued after the Italian economic miracle, in the latest years it was bought for its good position and with the idea to make it a beautiful first home with a big park all around. The renovation started and made the building structurally safe in the respect the anti-seismic rules, then the renovation stopped due to a lack of money. Now the owner is ready to complete the house and this situation creates the opportunity to do the study of the best solution to save the climate and save money.

The building is a two-story house, where the ground floor is used as garage and toolshed, the first floor is the residential part.

Position and climate data

The building is located in Cumiana (Turin).

The town is classified as E region with 2829 heating day-degree. During the cold season (15th October – 15th April) the average temperature is around 5 °C and the average minimum in the coldest months is -8.8 °C. In the hot season (18th April – 8th October) usually the temperature oscillates between 11 and 31 °C. Average wind speed is 1.4m/s.

The building doesn't suffer from artificial shadowing due to nearby obstacles.

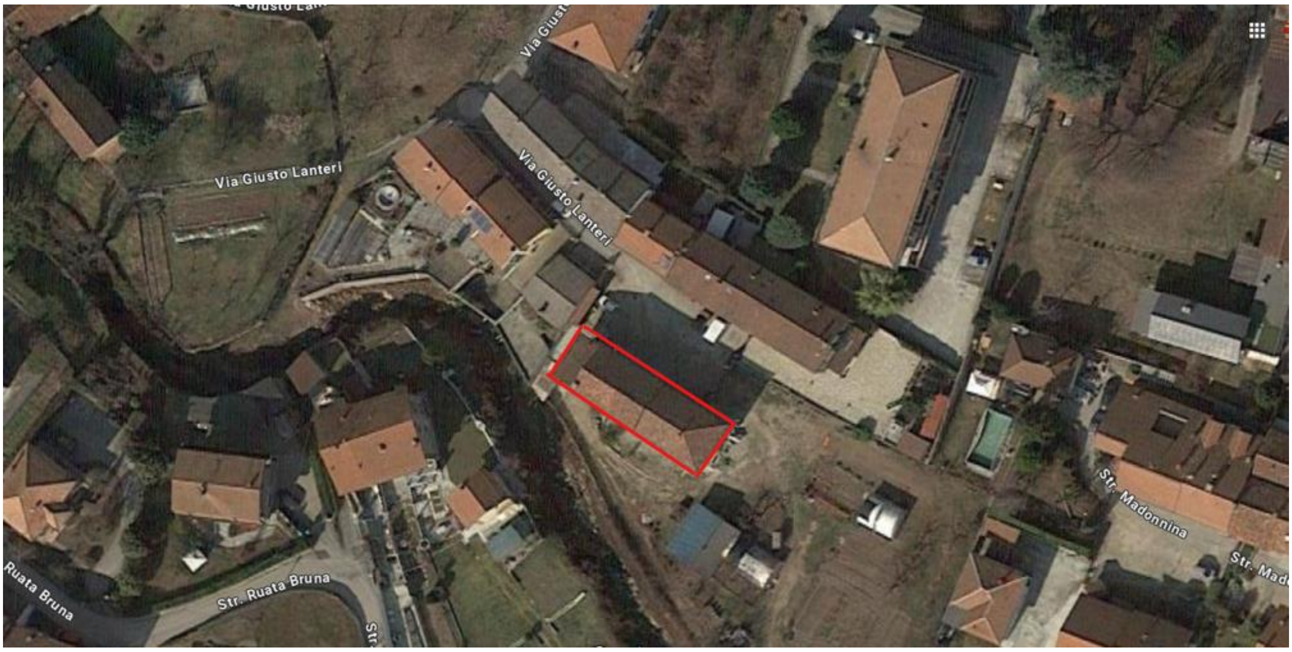


Figure 5. Satellite view of the building

Site inspection and planimetry

By the site inspection, all the measurement and the walls stratigraphy data were acquired.

Figure 6. Front view of the building

Figure 7. Side view of the building

Figure 8. Back view of the building

The planimetries are reported below.

The notation used is:

- Green lines are for external walls;
- Yellow lines for internal walls;
- Red lines are for some details: such as the roof outlines or the segments that mark a different stratigraphy for the wall;
- Lengths are in centimeters.

Ground floor

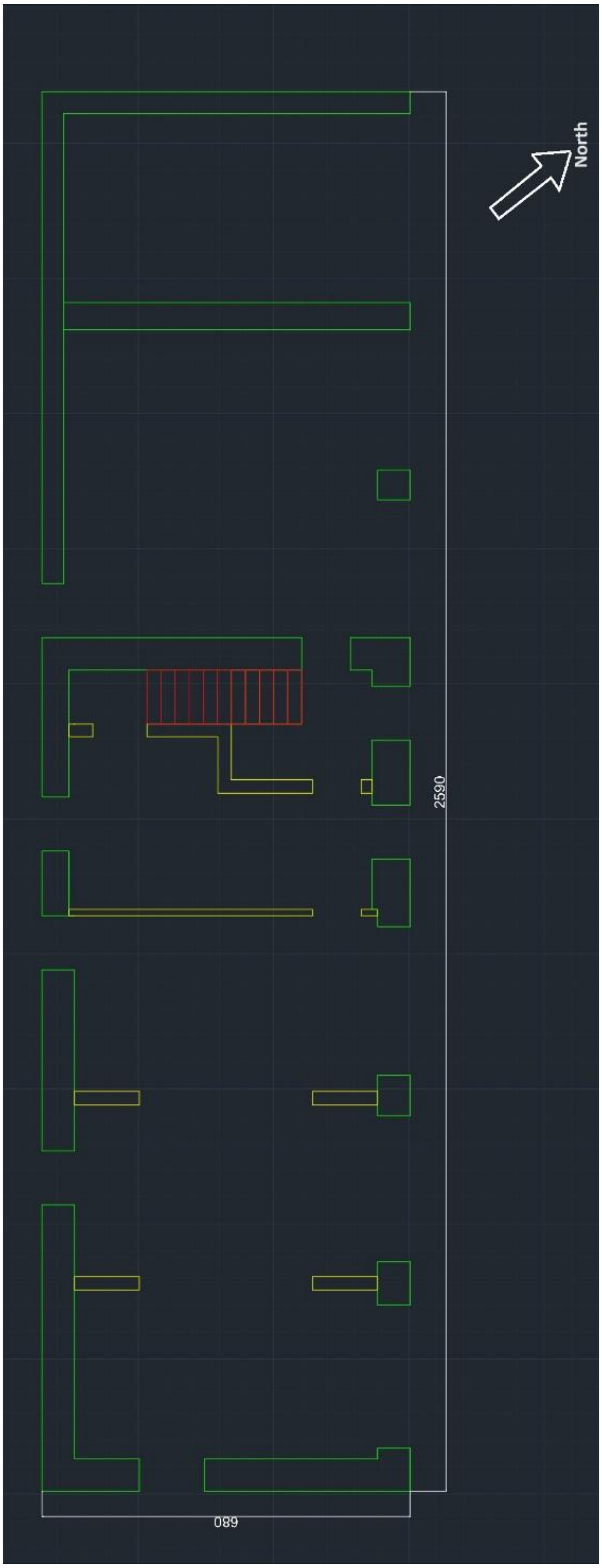


Figure 9. Ground floor planimetry

First floor

<u>It has a floor area of 136.5 m^2</u>.

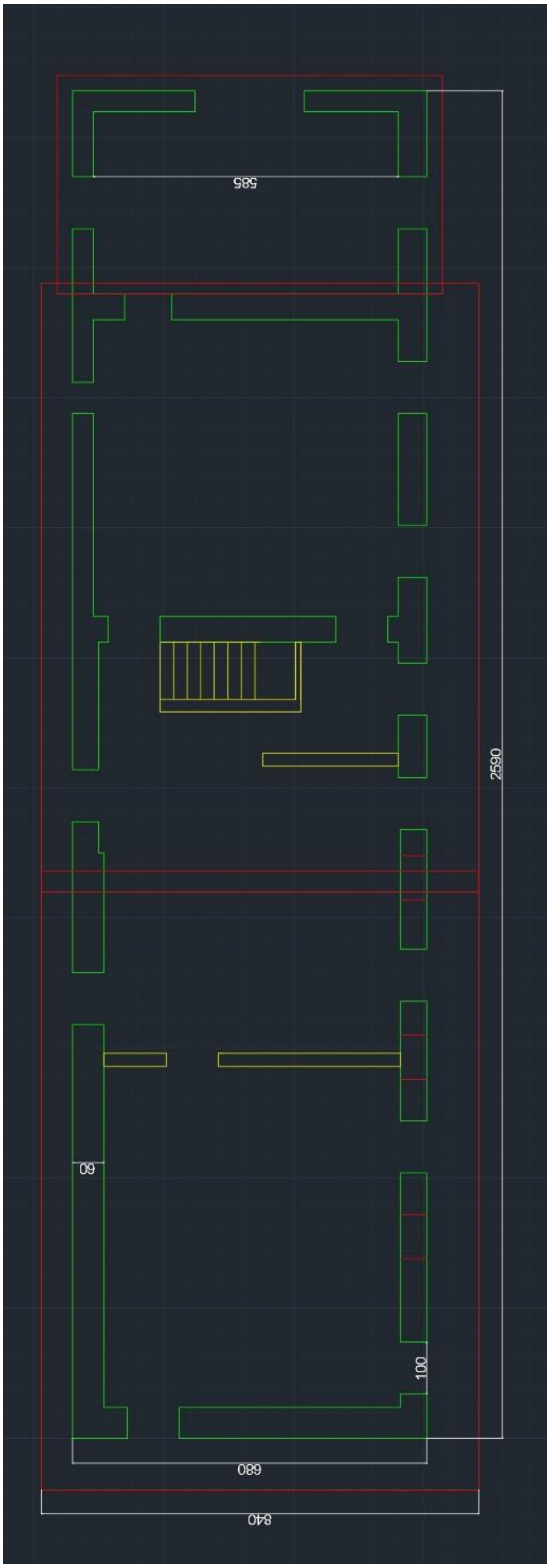


Figure 10. First floor planimetry

Putting all together it is possible to create a 3D model of the building.

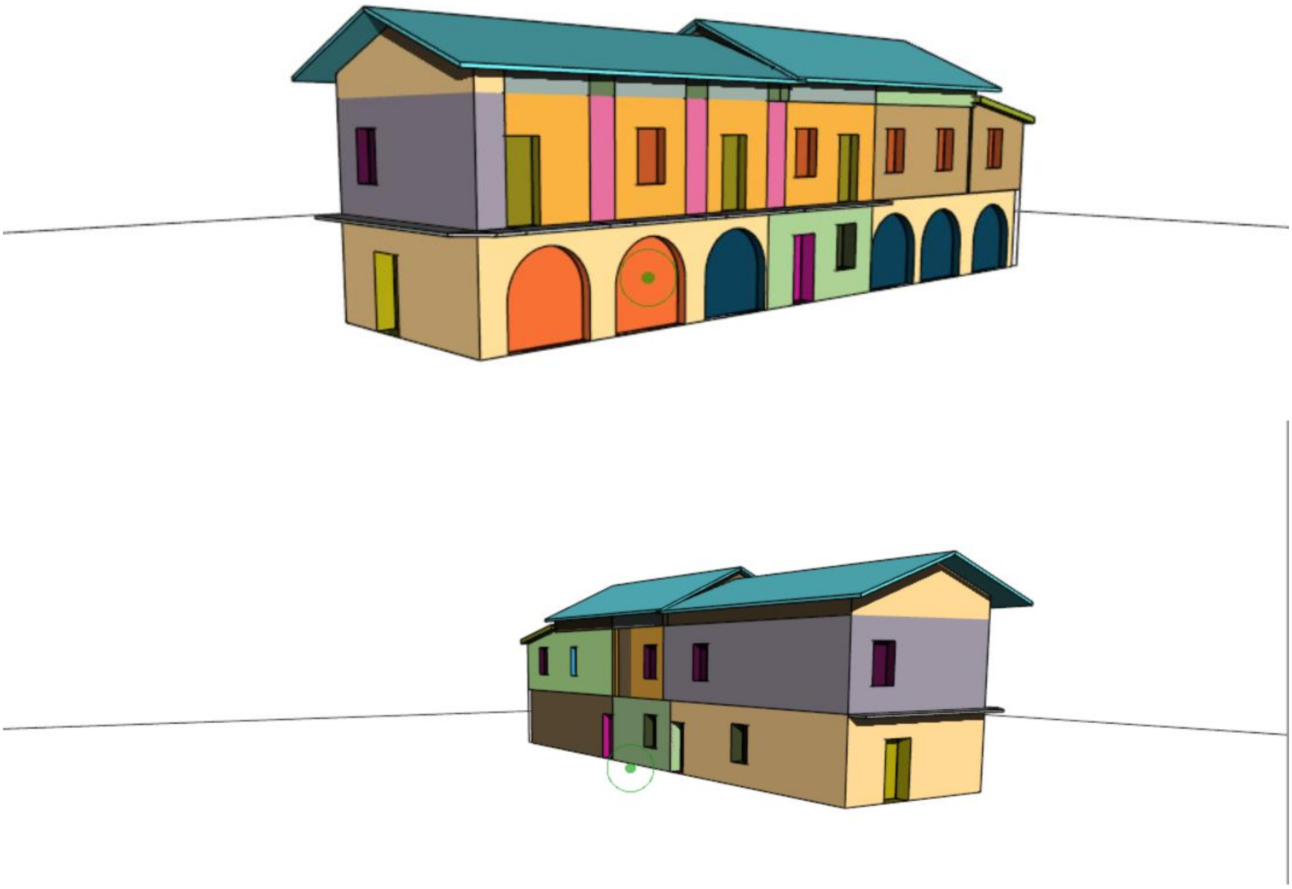


Figure 11. 3D model as generated by EdilClima. It is used a different color for each wall stratigraphy.

Walls and Structures description for the energetic model

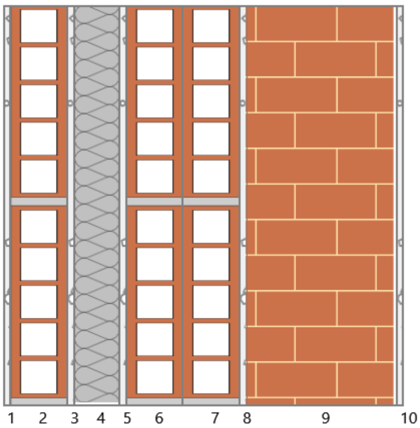
To create the energy model of the building it is necessary to know how the wall are.

During the in site inspection it was possible collecting all the necessary information about the walls' stratigraphy quite easily thanks to the fact the house is still under construction. When a photo can clearly show the wall feature, it is reported with the relative description.

Ground floor

Description: Wall A0

Thermal transmittance	***0,312***	W/m²K
Thickness	***535***	mm
Outdoor temperature	***-8,8***	°C
Permeance	***32,129***	10^{-12}kg/sm²Pa
Surface mass (with plaster)	***650***	kg/m²
Surface mass (without plaster)	***570***	kg/m²
Periodic transmittance	***0,011***	W/m²K
Attenuation factor	***0,035***	-
Thermal wave phase shift	***-19,6***	h



Stratigraphy:

N.	Description	s	Cond.	R	M.V.	C.T.	R.V.
1	Lime and sand plaster	*10,00*	*0,8000*	*0,013*	*1600*	*1,00*	*10*
2	6 HOLES 8 (interior wall)	*75,00*	*0,2880*	*0,260*	*825*	*1,00*	*5*
3	Lime and sand plaster	*10,00*	*0,8000*	*0,013*	*1600*	*1,00*	*10*
4	Sintered expanded polystyrene (graphite-like)	*60,00*	*0,0310*	*1,935*	*20*	*1,45*	*60*
5	Lime and sand plaster	*10,00*	*0,8000*	*0,013*	*1600*	*1,00*	*10*
6	21 HOLES 19 (interior wall)	*75,00*	*0,3000*	*0,250*	*979*	*1,00*	*5*
7	21 HOLE 19 (exterior wall)	*75,00*	*0,3150*	*0,238*	*979*	*1,00*	*5*
8	Lime and sand plaster	*10,00*	*0,8000*	*0,013*	*1600*	*1,00*	*10*
9	solid brick	*200,00*	*0,7780*	*0,257*	*1800*	*0,84*	*5*
10	Lime and sand plaster	*10,00*	*0,8000*	*0,013*	*1600*	*1,00*	*10*

Table 7. Wall Stratigraphy

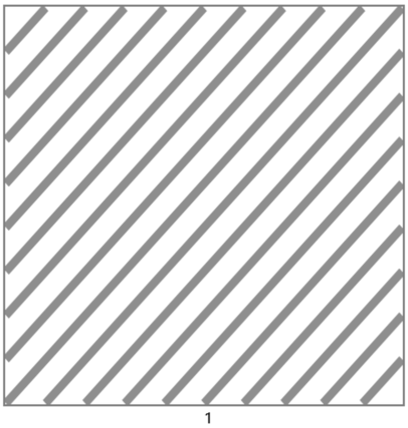
Caption

s	Thickness	mm
Cond.	Thermal conductivity, including any correction coefficients	W/mK
R	Thermal resistance	m^2K/W
M.V.	Mass density	kg/m^3
C.T.	Specific thermal capacity	kJ/kgK
R.V.	Vapor diffusion resistance factor in dry end	-

Figure 12. Photo of the wall

Description: Wall B0

Thermal transmittance	***2,164***	W/m^2K
Thickness	***600***	mm
Outdoor temperature	***-8,8***	°C
Permeance	***3,333***	$10^{-12}kg/sm^2Pa$
Surface mass (with plaster)	***1500***	kg/m^2
Surface mass (without plaster)	***1500***	kg/m^2
Periodic transmittance	***0,120***	W/m^2K
Attenuation factor	***0,056***	-
Thermal wave phase shift	***-15,4***	h



Stratigraphy:

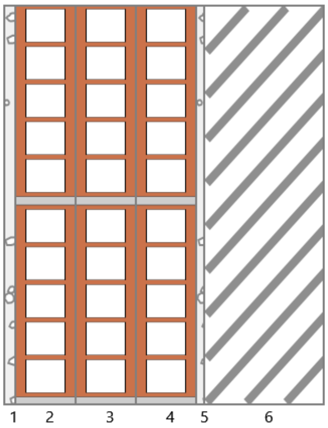
N.	Description	s	Cond.	R	M.V.	C.T.	R.V.
1	Natural stone masonry	*600,00*	*2,3000*	*0,261*	*2500*	*1,00*	*100*

Table 8. Wall Stratigraphy

Figure 13. Photo of the wall

Description: ***Wall D0***

Thermal transmittance	***0,954***	W/m²K
Thickness	***400***	mm
Outdoor temperature	***-8,8***	°C
Permeance	***12,214***	10^{-12}kg/sm²Pa
Surface mass (with plaster)	***635***	kg/m²
Surface mass (without plaster)	***595***	kg/m²
Periodic transmittance	***0,129***	W/m²K
Attenuation factor	***0,136***	-
Thermal wave phase shift	***-13,9***	h



Stratigraphy:

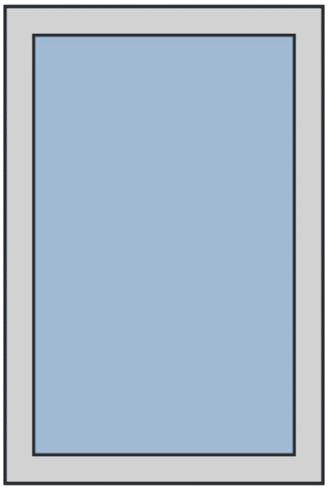
N.	Description	s	Cond.	R	M.V.	C.T.	R.V.
1	Lime and sand plaster	*15,00*	*0,8000*	*0,019*	*1600*	*1,00*	*10*
2	21 HOLE 19 (interior wall)	*75,00*	*0,3000*	*0,250*	*979*	*1,00*	*5*
3	21 HOLE 19 (interior wall)	*75,00*	*0,3000*	*0,250*	*979*	*1,00*	*5*
4	21 HOLE 19 (interior wall)	*75,00*	*0,3000*	*0,250*	*979*	*1,00*	*5*
5	Lime and sand plaster	*10,00*	*0,8000*	*0,013*	*1600*	*1,00*	*10*
6	Natural stone masonry	*150,00*	*2,3000*	*0,065*	*2500*	*1,00*	*100*

Table 9., Wall Stratigraphy

Figure 14. Photo of the wall

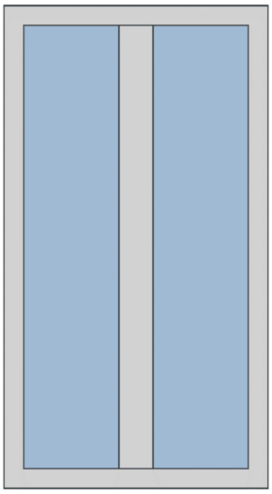
All windows data are taken from "Fascicolo sulla tipologia edilizia italiana"[22].

Description: ***Window 100 x 150***



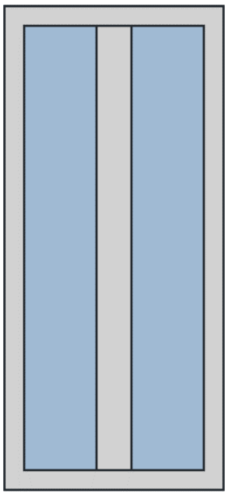
Feature			
Thermal transmittance	U_w	***4,900***	W/m²K
Glass transmittance	U_g	***5,000***	W/m²K
Solar contribute and shadowing			
Emissivity	ε	***0,837***	-
Solar transmittance factor	$g_{gl,n}$	***0,850***	-
Shadow factor(winter)	$f_{c\ inv}$	***1,00***	-
Shadow factor (summer)	$f_{c\ est}$	***1,00***	-
Size			
Width		***100,0***	cm
Height		***150,0***	cm
Frame			
Area	A_w	***1,500***	m²
Glass area	A_g	***1,082***	m²
Frame area	A_f	***0,418***	m²
Shape factor	F_f	***0,72***	-
Glass perimeter	L_g	***4,280***	m
Frame perimeter	L_f	***5,000***	m

Description: ***Window 120 x 220***



Feature			
Thermal transmittance	U_w	***4,900***	W/m²K
Glass transmittance	U_g	***5,000***	W/m²K
Solar contribute and shadowing			
Emissivity	ε	***0,837***	-
Solar transmittance factor	$g_{gl,n}$	***0,850***	-
Shadow factor(winter)	$f_{c\ inv}$	***1,00***	-
Shadow factor (summer)	$f_{c\ est}$	***1,00***	-
Size			
Width		***120,0***	cm
Height		***220,0***	cm
Frame			
Area	A_w	***2,640***	m²
Glass area	A_g	***1,757***	m²
Frame area	A_f	***0,883***	m²
Shape factor	F_f	***0,67***	-
Glass perimeter	L_g	***9,820***	m
Frame perimeter	L_f	***6,800***	m

Description: ***Window 100 x 220***

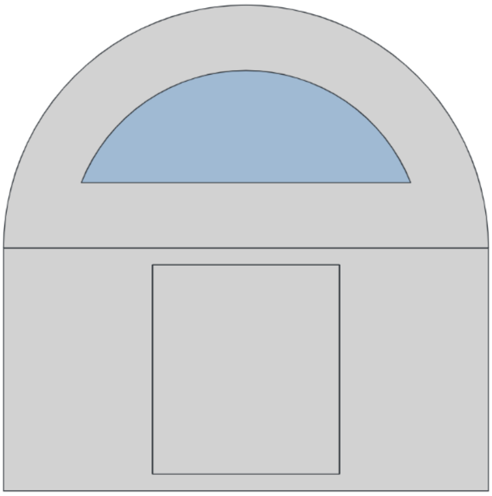


Feature			
Thermal transmittance	U_w	***4,900***	W/m^2K
Glass transmittance	U_g	***5,000***	W/m^2K
Solar contribute and shadowing			
Emissivity	ε	***0,837***	-
Solar transmittance factor	$g_{gl,n}$	***0,850***	-
Shadow factor(winter)	$f_{c\ inv}$	***1,00***	-
Shadow factor (summer)	$f_{c\ est}$	***1,00***	-
Size			
Width		***100,0***	cm
Height		***220,0***	cm
Frame			
Area	A_w	***2,200***	m^2
Glass area	A_g	***1,353***	m^2
Frame area	A_f	***0,847***	m^2
Shape factor	F_f	***0,62***	-
Glass perimeter	L_g	***9,420***	m
Frame perimeter	L_f	***6,400***	m

Descrption: ***Garage door wood***

Feature

Thermal transmittance	U_w	***1,315***	W/m^2K
Glass transmittance	U_g	***1,100***	W/m^2K



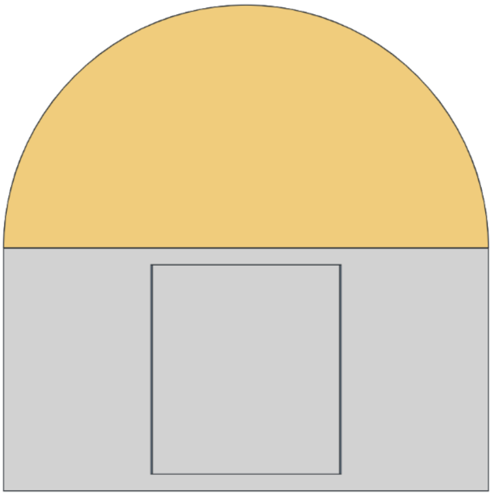
Size

Width	***260,0***	cm
Height	***260,0***	cm

Descrption: ***Garage door pvc***

Feature

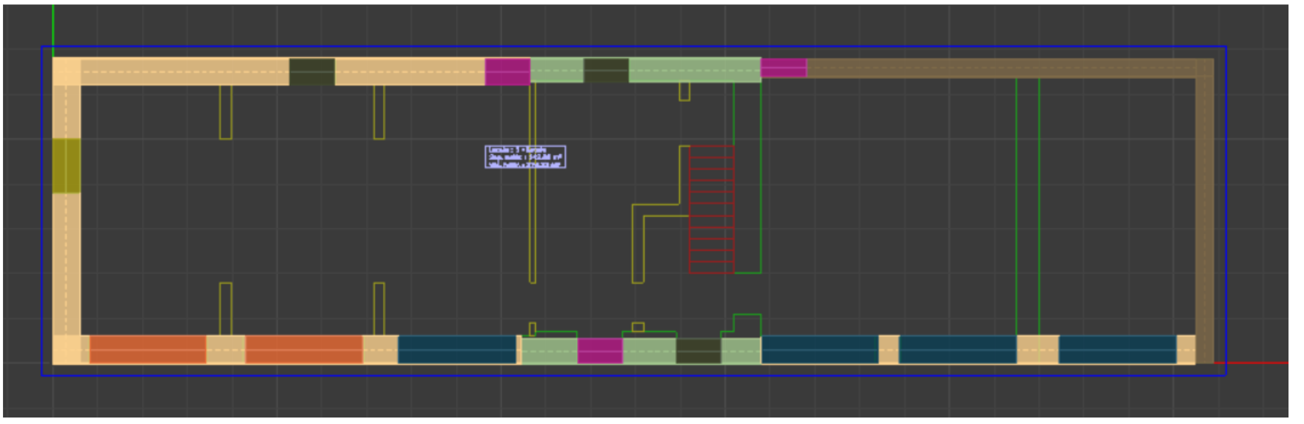
Thermal transmittance	U_w	***1,063***	W/m^2K



Size

Width	***260,0***	cm
Height	***260,0***	cm

A colored planimetry shows where the various structures are positioned.



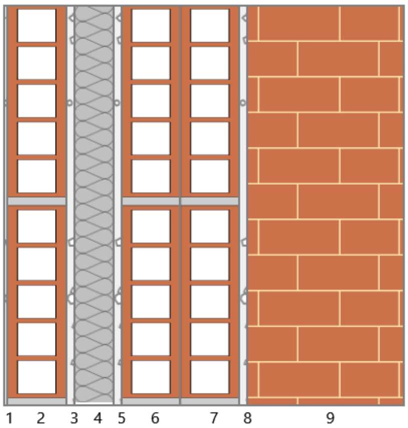
Color	Description
	Wall A0
	Wall B0
	Wall D0
	Window 120x220 cm
	Window 100x220 cm
	Window 100x150 cm
	Garage door wood
	Garage door pvc

Figure 15. Colored planimetry to show the position of the various wall structures

First floor

<u>Description:</u> ***Wall A1 bricks***

Thermal transmittance	***0,350***	W/m²K
Thickness	***510***	mm
Outdoor temperature	***-8,8***	°C
Permeance	***33,927***	10^{-12}kg/sm²Pa
Surface mass (with plaster)	***633***	kg/m²
Surface mass (without plaster)	***570***	kg/m²
Periodic transmittance	***0,014***	W/m²K
Attenuation factor	***0,039***	-
Thermal wave phase shift	***-19,1***	h



<u>Stratigraphy:</u>

N.	Description	s	Cond.	R	M.V.	C.T.	R.V.
1	Lime mortar or lime and cement mortar	*5,00*	*0,9000*	*0,006*	*1800*	*1,00*	*22*
2	6 HOLES 8 (interior wall)	*75,00*	*0,2880*	*0,260*	*825*	*1,00*	*5*
3	Lime mortar or lime and cement mortar	*10,00*	*0,9000*	*0,011*	*1800*	*1,00*	*22*
4	Sintered expanded polystyrene (graphite-like)	*50,00*	*0,0310*	*1,613*	*20*	*1,45*	*60*
5	Lime mortar or lime and cement mortar	*10,00*	*0,9000*	*0,011*	*1800*	*1,00*	*22*
6	21 HOLE 19 (interior wall)	*75,00*	*0,3000*	*0,250*	*979*	*1,00*	*5*
7	21 HOLE 19 (exterior wall)	*75,00*	*0,3150*	*0,238*	*979*	*1,00*	*5*
8	Lime mortar or lime and cement mortar	*10,00*	*0,9000*	*0,011*	*1800*	*1,00*	*22*
9	solid brick	*200,00*	*0,7780*	*0,257*	*1800*	*0,84*	*5*

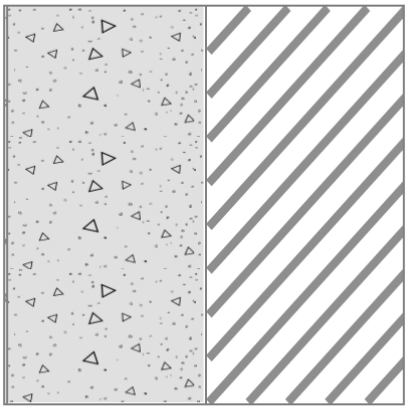
Table 10. Wall Stratigraphy

<u>Caption</u>

s	Thickness	mm
Cond.	Thermal conductivity, including any correction coefficients	W/mK
R	Thermal resistance	m²K/W
M.V.	Mass density	kg/m³
C.T.	Specific thermal capacity	kJ/kgK
R.V.	Vapor diffusion resistance factor in dry end	-

Figure 16. Photo of the wall

Description: ***Wall A1 reinforced concrete***



Thermal transmittance	***2,357***	W/m^{2}K
Thickness	***505***	mm
Outdoor temperature	***-8,8***	°C
Permeance	***3,472***	10^{-12}kg/sm^{2}Pa
Surface mass (with plaster)	***1209***	kg/m^2
Surface mass (without plaster)	***1200***	kg/m^2
Periodic transmittance	***0,232***	W/m^{2}K
Attenuation factor	***0,098***	-
Thermal wave phase shift	***-12,8***	h

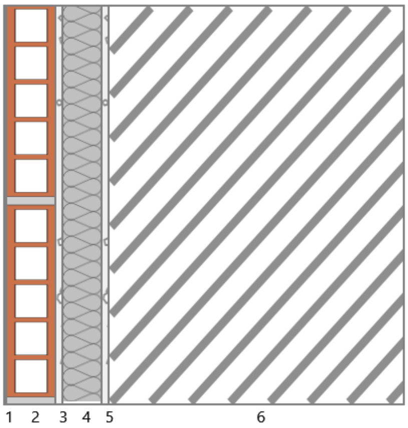
Stratigraphy:

N.	Descrizione strato	s	Cond.	R	M.V.	C.T.	R.V.
1	Lime mortar or lime and cement mortar	*5,00*	*0,9000*	*0,006*	*1800*	*1,00*	*22*
2	Reinforced c.l.s. (1% steel)	*250,00*	*2,3000*	*0,109*	*2300*	*1,00*	*130*
3	Natural stone masonry	*250,00*	*2,3000*	*0,109*	*2500*	*1,00*	*100*

Table 11. Wall Stratigraphy

Description: ***Wall A1 stone***

Thermal transmittance	*0,392*	W/m^2K
Thickness	*610*	mm
Outdoor temperature	*-8,8*	°C
Permeance	*4,038*	$10^{-12}kg/sm^2Pa$
Surface mass (with plaster)	*1244*	kg/m^2
Surface mass (without plaster)	*1199*	kg/m^2
Periodic transmittance	*0,012*	W/m^2K
Attenuation factor	*0,030*	-
Thermal wave phase shift	*-17,6*	h



Stratigraphy:

N.	Description	s	Cond.	R	M.V.	C.T.	R.V.
1	Lime mortar or lime and cement mortar	5,00	0,9000	0,006	1800	1,00	22
2	21 HOLE 19 (interior wall)	75,00	0,3000	0,250	979	1,00	5
3	Lime mortar or lime and cement mortar	10,00	0,9000	0,011	1800	1,00	22
4	Sintered expanded polystyrene (graphite-like)	60,00	0,0320	1,875	15	1,45	60
5	Lime mortar or lime and cement mortar	10,00	0,9000	0,011	1800	1,00	22
6	Natural stone masonry	450,00	2,3000	0,196	2500	1,00	100

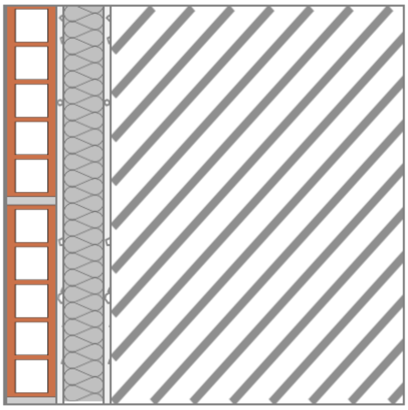
Table 12. Wall Stratigraphy

In this case the photos shows some bricks on the external layer, but this is only for the frame around a window, the wall is made by stones as also possible to notice in the photo of the house façade.

Figure 17. Photo of the wall

Description: ***Wall B1***

Thermal transmittance	***0,384***	W/m²K
Thickness	***600***	mm
Outdoor temperature	***-8,8***	°C
Permeance	***4,122***	10^{-12}kg/sm²Pa
Surface mass (with plaster)	***1220***	kg/m²
Surface mass (without plaster)	***1175***	kg/m²
Periodic transmittance	***0,012***	W/m²K
Attenuation factor	***0,032***	-
Thermal wave phase shift	***-17,5***	h



Stratigraphy:

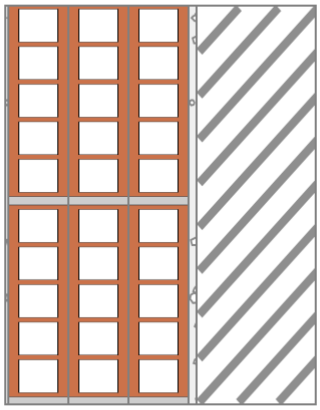
N.	Description	s	Cond.	R	M.V.	C.T.	R.V.
1	Lime mortar or lime and cement mortar	*5,00*	*0,9000*	*0,006*	*1800*	*1,00*	*22*
2	21 HOLE 19 (interior wall)	*75,00*	*0,3000*	*0,250*	*979*	*1,00*	*5*
3	Lime mortar or lime and cement mortar	*10,00*	*0,9000*	*0,011*	*1800*	*1,00*	*22*
4	Sintered expanded polystyrene (graphite-like)	*60,00*	*0,0310*	*1,935*	*20*	*1,45*	*60*
5	Lime mortar or lime and cement mortar	*10,00*	*0,9000*	*0,011*	*1800*	*1,00*	*22*
6	Natural stone masonry	*440,00*	*2,3000*	*0,191*	*2500*	*1,00*	*100*

Table 13. Wall Stratigraphy

Figure 18. Photo of the Wall

Description: ***Wall D1***

Thermal transmittance	***0,968***	W/m²K
Thickness	***390***	mm
Outdoor temperature	***-8,8***	°C
Permeance	***12,154***	10^{-12}kg/sm²Pa
Surface mass (with plaster)	***622***	kg/m²
Surface mass (without plaster)	***595***	kg/m²
Periodic transmittance	***0,139***	W/m²K
Attenuation factor	***0,144***	-
Thermal wave phase shift	***-13,5***	h



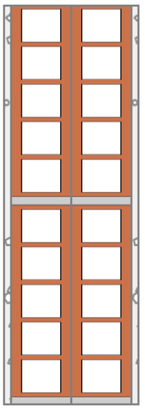
Stratigraphy:

N.	Descrizione strato	s	Cond.	R	M.V.	C.T.	R.V.
1	Lime mortar or lime and cement mortar	*5,00*	*0,9000*	*0,006*	*1800*	*1,00*	*22*
2	21 HOLE 19 (interior wall)	*75,00*	*0,3000*	*0,250*	*979*	*1,00*	*5*
3	21 HOLE 19 (interior wall)	*75,00*	*0,3000*	*0,250*	*979*	*1,00*	*5*
4	21 HOLE 19 (interior wall)	*75,00*	*0,3000*	*0,250*	*979*	*1,00*	*5*
5	Lime mortar or lime and cement mortar	*10,00*	*0,9000*	*0,011*	*1800*	*1,00*	*22*
6	Natural stone masonry	*150,00*	*2,3000*	*0,065*	*2500*	*1,00*	*100*

Table 14. Wall Stratigraphy

Description: ***internal wall***

Thermal transmittance	***1,204***	W/m²K
Thickness	***170***	mm
Outdoor temperature	***20,0***	°C
Permeance	***210,526***	10^{-12}kg/sm²Pa
Surface mass (with plaster)	***169***	kg/m²
Surface mass (without plaster)	***137***	kg/m²
Periodic transmittance	***0,691***	W/m²K
Attenuation factor	***0,574***	-
Thermal wave phase shift	***-6,3***	h

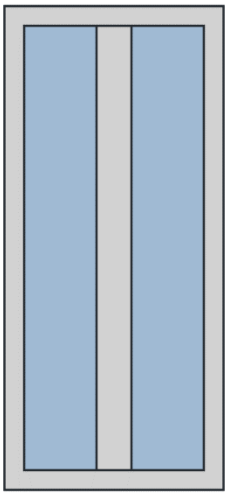


Stratigraphy:

N.	Descrizione strato	s	Cond.	R	M.V.	C.T.	R.V.
1	Lime and sand plaster	*10,00*	*0,8000*	*0,013*	*1600*	*1,00*	*10*
2	6 HOLES 6 (interior wall)	*75,00*	*0,2750*	*0,273*	*911*	*1,00*	*5*
3	6 HOLES 6 (interior wall)	*75,00*	*0,2750*	*0,273*	*911*	*1,00*	*5*
4	Plaster of lime and sand	*10,00*	*0,8000*	*0,013*	*1600*	*1,00*	*10*

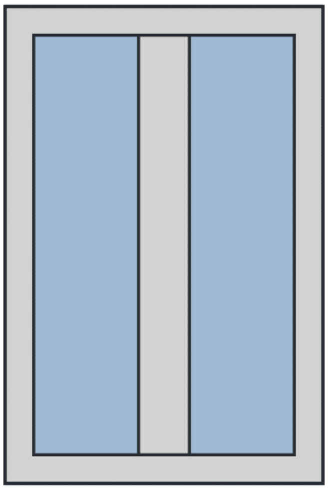
Table 15. Wall Stratigraphy

Description: ***Window 100 x 220***



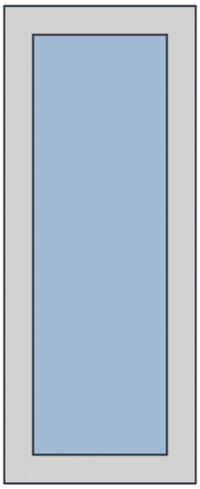
Feature			
Thermal transmittance	U_w	***4,900***	W/m^2K
Glass transmittance	U_g	***5,000***	W/m^2K
Solar contribute and shadowing			
Emissivity	ε	***0,837***	-
Solar transmittance factor	$g_{gl,n}$	***0,850***	-
Shadow factor(winter)	$f_{c\ inv}$	***1,00***	-
Shadow factor (summer)	$f_{c\ est}$	***1,00***	-
Size			
Width		***100,0***	cm
Height		***220,0***	cm
Frame			
Area	A_w	***2,200***	m^2
Glass area	A_g	***1,353***	m^2
Frame area	A_f	***0,847***	m^2
Shape factor	F_f	***0,62***	-
Glass perimeter	L_g	***9,420***	m
Frame perimeter	L_f	***6,400***	m
Thermal bridge			
Linear thermal transmittance	Ψ	***0,278***	W/mK
Perimeter		***6,40***	m

Description: ***Window 100 x 150***



Feature			
Thermal transmittance	U_w	***4,900***	W/m²K
Glass transmittance	U_g	***5,000***	W/m²K
Solar contribute and shadowing			
Emissivity	ε	***0,837***	-
Solar transmittance factor	$g_{gl,n}$	***0,850***	-
Shadow factor(winter)	$f_{c\ inv}$	***1,00***	-
Shadow factor (summer)	$f_{c\ est}$	***1,00***	-
Size			
Width		***100,0***	cm
Height		***150,0***	cm
Frame			
Area	A_w	***1,500***	m²
Glass area	A_g	***0,884***	m²
Frame area	A_f	***0,616***	m²
Shape factor	F_f	***0,59***	-
Glass perimeter	L_g	***6,620***	m
Frame perimeter	L_f	***5,000***	m
Thermal bridge			
Linear thermal transmittance	Ψ	***0,278***	W/mK
Perimeter		***5,00***	m

Description: ***Window 60 x 150***



Feature

Thermal transmittance	U_w	***4,900***	W/m²K
Glass transmittance	U_g	***5,000***	W/m²K

Solar contribute and shadowing

Emissivity	ε	***0,837***	-
Solar transmittance factor	$g_{gl,n}$	***0,850***	-
Shadow factor(winter)	$f_{c\ inv}$	***1,00***	-
Shadow factor (summer)	$f_{c\ est}$	***1,00***	-

Size

Width		***60,0***	cm
Height		***150,0***	cm

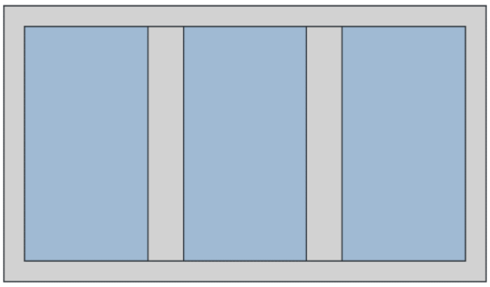
Frame

Area	A_w	***0,900***	m²
Glass area	A_g	***0,554***	m²
Frame area	A_f	***0,346***	m²
Shape factor	F_f	***0,62***	-
Glass perimeter	L_g	***3,480***	m
Frame perimeter	L_f	***4,200***	m

Thermal bridge

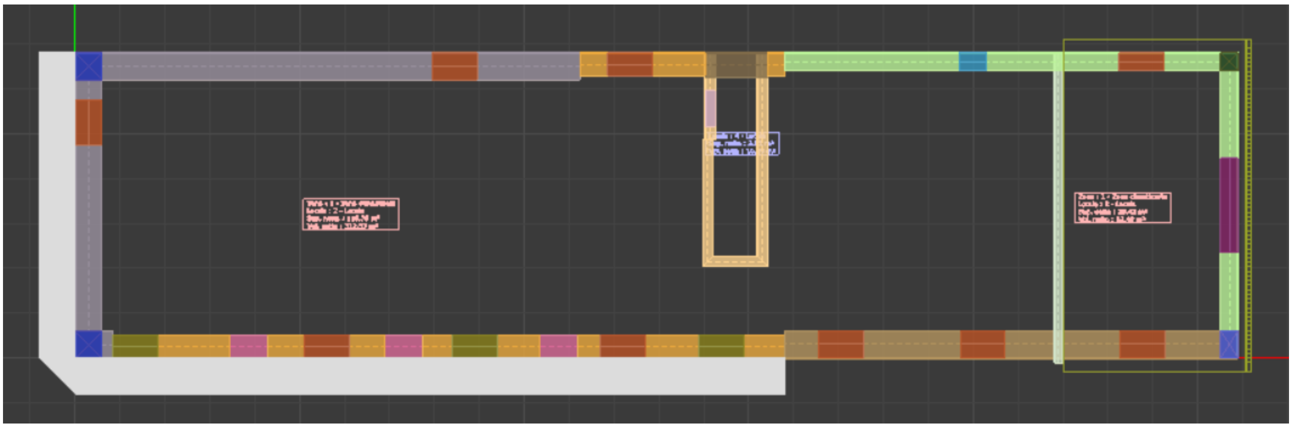
Linear thermal transmittance	Ψ	***0,278***	W/mK
Perimeter		***4,20***	m

Description: ***Window 210 x 120***



Feature			
Thermal transmittance	U_w	***4,900***	W/m²K
Glass transmittance	U_g	***5,000***	W/m²K
Solar contribute and shadowing			
Emissivity	ε	***0,837***	-
Solar transmittance factor	$g_{gl,n}$	***0,850***	-
Shadow factor(winter)	$f_{c\ inv}$	***1,00***	-
Shadow factor (summer)	$f_{c\ est}$	***1,00***	-
Size			
Width		***100,0***	cm
Height		***150,0***	cm
Frame			
Area	A_w	***2,520***	m²
Glass area	A_g	***1,652***	m²
Frame area	A_f	***0,868***	m²
Shape factor	F_f	***0,66***	-
Glass perimeter	L_g	***9,360***	m
Frame perimeter	L_f	***6,600***	m
Thermal bridge			
Linear thermal transmittance	Ψ	***0,278***	W/mK
Perimeter		***6,60***	m

A colored planimetry shows where the various structures are positioned.



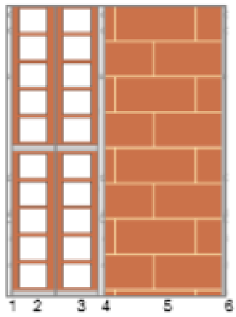
Color	Description
	Wall A1 bricks
	Wall A1 reinforced concrete
	Wall A1 stone
	Wall B1
	Wall D1
	Internal wall
	Window 100x220 cm
	Window 100x150 cm
	Window 60x150 cm
	Window 210x120
	Balcony

Figure 19. Colored planimetry to show the position of the various wall structures

Non livable attic

Description: *Wall A2 bricks*

Thermal transmittance	***1,050***	W/m^{2}K
Thickness	***380***	mm
Outdoor temperature	***-8,8***	°C
Permeance	***33,927***	10^{-12}kg/sm^{2}Pa
Surface mass (with plaster)	***555***	kg/m^2
Surface mass (without plaster)	***507***	kg/m^2
Periodic transmittance	***0,157***	W/m^{2}K
Attenuation factor	***0,039***	-
Thermal wave phase shift	***-12,9***	h



Stratigraphy:

N.	Description	s	Cond.	R	M.V.	C.T.	R.V.
5	Lime mortar or lime and cement mortar	*10,00*	*0,9000*	*0,011*	*1800*	*1,00*	*22*
6	21 HOLE 19 (interior wall)	*75,00*	*0,3000*	*0,250*	*979*	*1,00*	*5*
7	21 HOLE 19 (exterior wall)	*75,00*	*0,3150*	*0,238*	*979*	*1,00*	*5*
8	Lime mortar or lime and cement mortar	*10,00*	*0,9000*	*0,011*	*1800*	*1,00*	*22*
9	solid brick	*200,00*	*0,7780*	*0,257*	*1800*	*0,84*	*5*

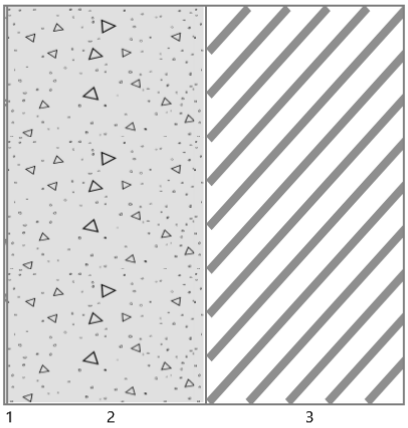
Table 16 Wall Stratigraphy

Caption

s	Thickness	mm
Cond.	Thermal conductivity, including any correction coefficients	W/mK
R	Thermal resistance	m^{2}K/W
M.V.	Mass density	kg/m^3
C.T.	Specific thermal capacity	kJ/kgK
R.V.	Vapor diffusion resistance factor in dry end	-

Description: ***Wall A2 reinforced concrete***

Thermal transmittance	***2,357***	W/m²K
Thickness	***505***	mm
Outdoor temperature	***-8,8***	°C
Permeance	***3,472***	10^{-12}kg/sm²Pa
Surface mass (with plaster)	***1209***	kg/m²
Surface mass (without plaster)	***1200***	kg/m²
Periodic transmittance	***0,232***	W/m²K
Attenuation factor	***0,098***	-
Thermal wave phase shift	***-12,8***	h



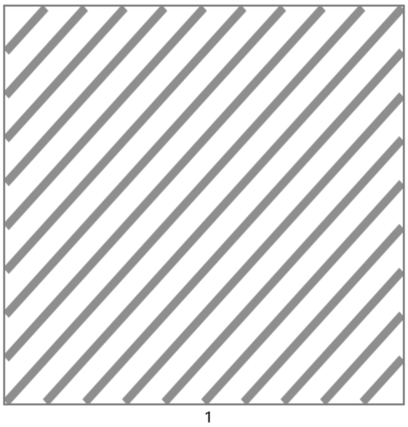
Stratigraphy:

N.	Descrizione strato	s	Cond.	R	M.V.	C.T.	R.V.
1	Lime mortar or lime and cement mortar	*5,00*	*0,9000*	*0,006*	*1800*	*1,00*	*22*
2	Reinforced c.l.s. (1% steel)	*250,00*	*2,3000*	*0,109*	*2300*	*1,00*	*130*
3	Natural stone masonry	*250,00*	*2,3000*	*0,109*	*2500*	*1,00*	*100*

Table 17. Wall Stratigraphy

Description: ***Wall A2 stone***

Thermal transmittance	***2,654***	W/m²K
Thickness	***460***	mm
Outdoor temperature	***-8,8***	°C
Permeance	***4,424***	10^{-12}kg/sm²Pa
Surface mass (with plaster)	***1143***	kg/m²
Surface mass (without plaster)	***1125***	kg/m²
Periodic transmittance	***0,282***	W/m²K
Attenuation factor	***0,115***	-
Thermal wave phase shift	***-12,5***	h



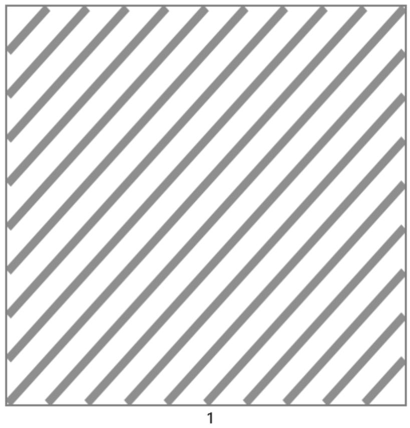
Stratigraphy:

N.	Description	s	Cond.	R	M.V.	C.T.	R.V.
5	Lime mortar or lime and cement mortar	*10,00*	*0,9000*	*0,011*	*1800*	*1,00*	*22*
6	Natural stone masonry	*450,00*	*2,3000*	*0,196*	*2500*	*1,00*	*100*

Table 18. Wall Stratigraphy

Description: Wall B2

Thermal transmittance	***2,164***	W/m^2K
Thickness	***600***	mm
Outdoor temperature	***-8,8***	°C
Permeance	***3,333***	$10^{-12}kg/sm^2Pa$
Surface mass (with plaster)	***1500***	kg/m^2
Surface mass (without plaster)	***1500***	kg/m^2
Periodic transmittance	***0,120***	W/m^2K
Attenuation factor	***0,056***	-
Thermal wave phase shift	***-15,4***	h



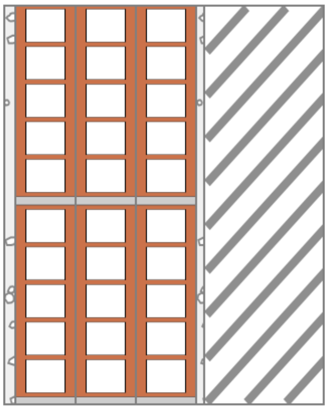
Stratigraphy:

N.	Description	s	Cond.	R	M.V.	C.T.	R.V.
1	Natural stone masonry	*600,00*	*2,3000*	*0,261*	*2500*	*1,00*	*100*

Table 19. Wall Stratigraphy

Description: *Wall D2*

Thermal transmittance	***0,954***	W/m²K
Thickness	***400***	mm
Outdoor temperature	***-8,8***	°C
Permeance	***12,214***	10^{-12}kg/sm²Pa
Surface mass (with plaster)	***635***	kg/m²
Surface mass (without plaster)	***595***	kg/m²
Periodic transmittance	***0,129***	W/m²K
Attenuation factor	***0,136***	-
Thermal wave phase shift	***-13,9***	h

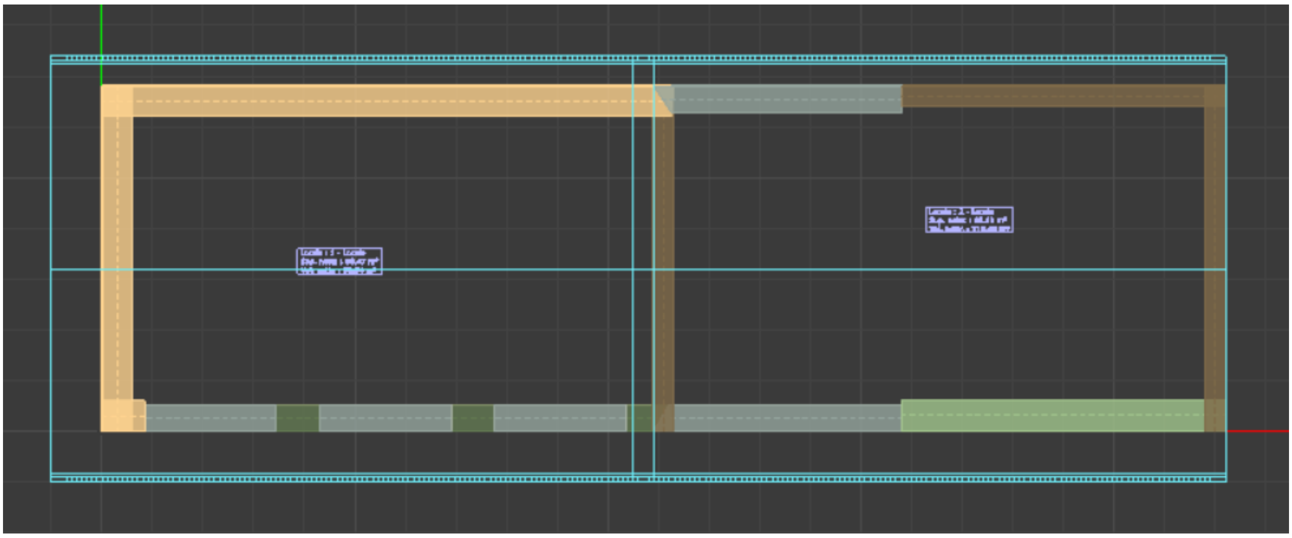


Stratigraphy:

N.	Description	s	Cond.	R	M.V.	C.T.	R.V.
1	Lime and sand plaster	*15,00*	*0,8000*	*0,019*	*1600*	*1,00*	*10*
2	21 HOLE 19 (interior wall)	*75,00*	*0,3000*	*0,250*	*979*	*1,00*	*5*
3	21 HOLE 19 (interior wall)	*75,00*	*0,3000*	*0,250*	*979*	*1,00*	*5*
4	21 HOLE 19 (interior wall)	*75,00*	*0,3000*	*0,250*	*979*	*1,00*	*5*
5	Lime and sand plaster	*10,00*	*0,8000*	*0,013*	*1600*	*1,00*	*10*
6	Natural stone masonry	*150,00*	*2,3000*	*0,065*	*2500*	*1,00*	*100*

Table 20. Wall Stratigraphy

A colored planimetry shows where the various structures are positioned.



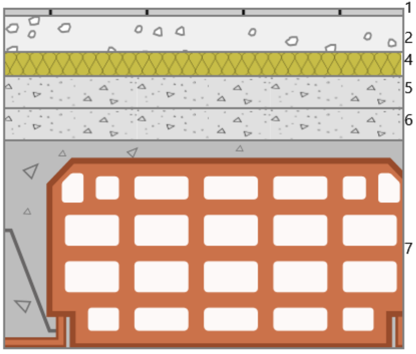
Color	Description
	Wall A2 bricks
	Wall A2 reinforced concrete
	Wall A2 stone
	Wall B2
	Wall D2

Figure 20. Colored planimetry showing the position of the various wall structures

Horizontal structures

Description: ***First floor structure***

Thermal transmittance	***0,614***	W/m²K
Thickness	***425***	mm
Outdoor temperature	***-2,8***	°C
Permeance	***0,002***	10^{-12}kg/sm²Pa
Surface mass (with plaster)	***593***	kg/m²
Surface mass (without plaster)	***593***	kg/m²
Periodic transmittance	***0,036***	W/m²K
Attenuation factor	***0,059***	-
Thermal wave phase shift	***-14,2***	h



Stratigraphy:

N.	Description	s	Cond.	R	M.V.	C.T.	R.V.
1	Ceramic tiles (tiles)	*10,00*	*1,3000*	*0,008*	*2300*	*0,84*	*9999999*
2	Self-levelling screed mix	*45,00*	*1,4000*	*0,032*	*1950*	*1,00*	*100*
3	Panel pipe - H30 (density 25 kg/mc)	*0,00*	-	-	-	-	-
4	Expanded polystyrene for CLASSIC FLOOR - PLAN FLOOR	*30,00*	*0,0350*	*0,857*	*25*	*1,21*	*70*
5	Concrete distribution screed with mesh	*40,00*	*1,4900*	*0,027*	*2200*	*0,88*	*70*
6	Reinforced c.l.s. (2% steel)	*40,00*	*2,5000*	*0,016*	*2400*	*1,00*	*130*
7	Floor block	*260,00*	*0,7430*	*0,350*	*1146*	*0,84*	*9*

Table 21. Floor stratigraphy

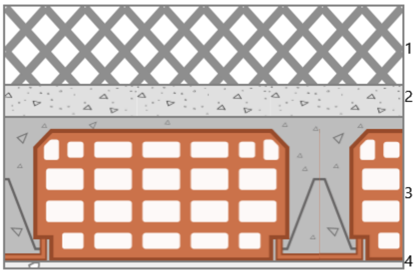
Caption

s	Thickness	mm
Cond.	Thermal conductivity, including any correction coefficients	W/mK
R	Thermal resistance	m²K/W
M.V.	Mass density	kg/m³
C.T.	Specific thermal capacity	kJ/kgK
R.V.	Vapor diffusion resistance factor in dry end	-

Figure 21. Photo of the floor structure seen from below

Description: ***attic floor structure***

Thermal transmittance	***1,135***	W/m²K
Thickness	***330***	mm
Outdoor temperature	***4,1***	°C
Permeance	***25,907***	10^{-12}kg/sm²Pa
Surface mass (with plaster)	***433***	kg/m²
Surface mass (without plaster)	***417***	kg/m²
Periodic transmittance	***0,202***	W/m²K
Attenuation factor	***0,178***	-
Thermal wave phase shift	***-10,7***	h



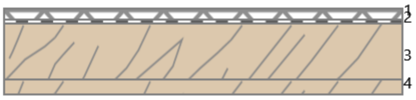
Stratigraphy:

N.	Description	s	Cond.	R	M.V.	C.T.	R.V.
1	Predosed Leca Lightweight Concrete	*100,00*	*0,4700*	*0,213*	*1500*	*1,00*	*8*
2	Reinforced c.l.s. (2% steel)	*40,00*	*2,5000*	*0,016*	*2400*	*1,00*	*130*
3	Attic block	*180,00*	*0,6000*	*0,300*	*950*	*0,84*	*9*
4	Lime and sand plaste	*10,00*	*0,8000*	*0,013*	*1600*	*1,00*	*10*

Table 22. Floor stratigraphy

Description: ***two-pitch roof***

Thermal transmittance	***0,472***	W/m^{2}K
Thickness	***109***	mm
Outdoor temperature	***-8,8***	°C
Permeance	***0,937***	10^{-12}kg/sm^{2}Pa
Surface mass (with plaster)	***55***	kg/m^2
Surface mass (without plaster)	***55***	kg/m^2
Periodic transmittance	***0,409***	W/m^{2}K
Attenuation factor	***0,868***	-
Thermal wave phase shift	***-3,8***	h



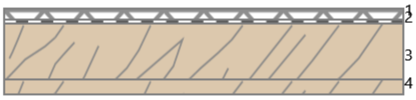
Stratigraphy:

N.	Descrizione strato	s	Cond.	R	M.V.	C.T.	R.V.
1	Terracotta tiles	*15,00*	*1,0000*	*0,015*	*2000*	*0,80*	*40*
2	Bitumen vapor barrier felt/foil	*4,00*	*0,2300*	*0,017*	*1100*	*1,00*	*50000*
3	Wood fiber	*70,00*	*0,0400*	*1,750*	*170*	*2,00*	*5*
4	Spruce wood flow perpend. to fibers	*20,00*	*0,1200*	*0,167*	*450*	*1,60*	*625*

Table 23. Roof stratigraphy

Description: ***one-pitch roof***

Thermal transmittance	***0,472***	W/m^{2}K
Thickness	***109***	mm
Outdoor temperature	***-8,8***	°C
Permeance	***0,937***	10^{-12}kg/sm^{2}Pa
Surface mass (with plaster)	***55***	kg/m^2
Surface mass (without plaster)	***55***	kg/m^2
Periodic transmittance	***0,409***	W/m^{2}K
Attenuation factor	***0,868***	-
Thermal wave phase shift	***-3,8***	h



Stratigrafia:

N.	Descrizione strato	s	Cond.	R	M.V.	C.T.	R.V.
1	Terracotta tiles	*15,00*	*1,0000*	*0,015*	*2000*	*0,80*	*40*
2	Bitumen vapor barrier felt/foil	*4,00*	*0,2300*	*0,017*	*1100*	*1,00*	*50000*
3	Wood fiber	*70,00*	*0,0400*	*1,750*	*170*	*2,00*	*5*
4	Spruce wood flow perpendicular to fibers	*20,00*	*0,1200*	*0,167*	*450*	*1,60*	*625*

Table 24. Roof stratigraphy

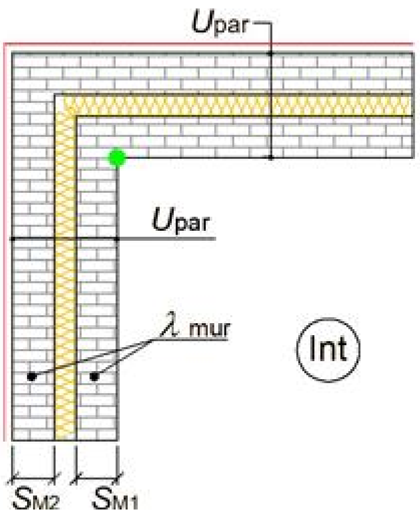
Thermal bridges

Creating a model to calculate the energy performance of buildings, thermal bridges have non negligible contribution. They are calculated following the reference standards UNI EN ISO 14683 e UNI EN ISO 10211.

Since in this case thermal bridges are similar, only one for each type is reported.

Description: ***Corner between walls (wall B1 -wall B1)***

Type	***Wall corner***	
Linear thermal transmittance for calculations	***-0,140***	W/mK
Reference linear thermal transmittance	***-0,280***	W/mK
Temperature factor frsi	***0,843***	-
Reference	***UNI EN ISO 14683 and UNI EN ISO 10211***	



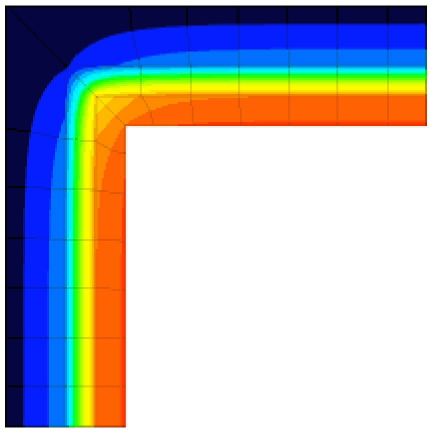
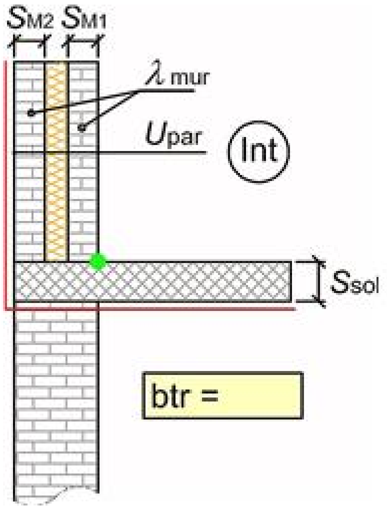


Figure 22. Thermal bridge description

Description: *Wall-floor intersection*

Type	***Wall- floor intersection***	
Linear thermal transmittance for calculations	***-0,595***	W/mK
Reference linear thermal transmittance	***-1,191***	W/mK
Temperature factor frsi	***0,473***	-
Reference	***UNI EN ISO 14683 e UNI EN ISO 10211***	



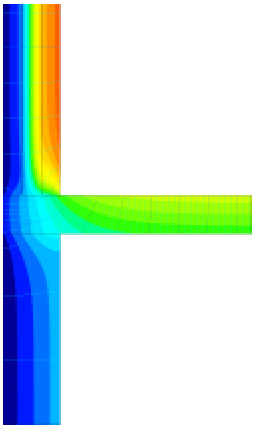
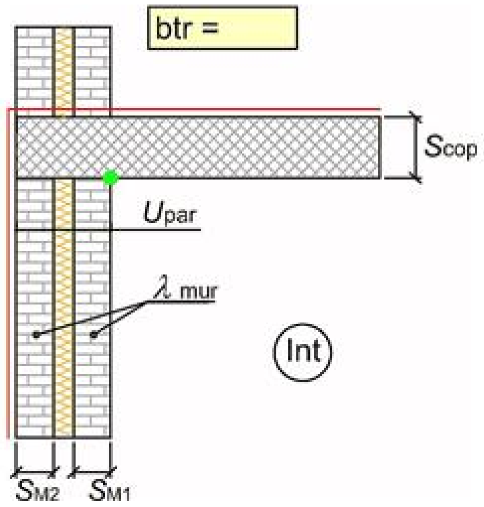


Figure 23. Thermal bridge description

Description: *Wall-ceiling intersection*

Type	***Wall-ceiling intersection***	
Linear thermal transmittance for calculations	***-0,630***	W/mK
Reference linear thermal transmittance	***-1,261***	W/mK
Temperature factor frsi	***0,597***	-
Reference	***UNI EN ISO 14683 e UNI EN ISO 10211***	



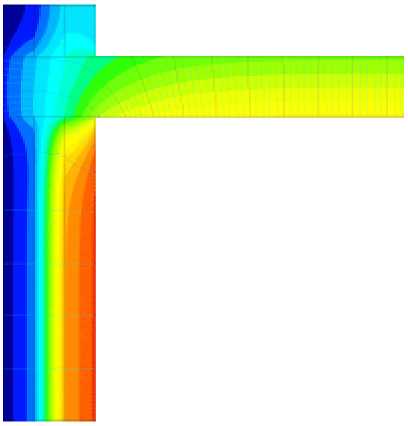


Figure 24. Thermal bridge description

Energy needs of the existing building

In order to assess the energy needs of the building, the calculations are performed with the aid of EdilClima. EdilClima is a software approved by the Italian authorities to model buildings and to create APE certificates.

Winter need

Cold season starts on 15th October and it ends onto 15th April

Month	n. of days	θe,m [°C]	Qh,tr [kWh]	Qh,r [kWh]	Qh,ve [kWh]	Qh,ht [kWh]	Qsol,w [kWh]	Qint [kWh]	Qgn [kWh]	Qh,nd [kWh]
October	17	10,2	928	268	151	1346	282	184	465	882
November	30	6,1	2925	449	376	3751	291	324	615	3136
December	31	1,9	4095	534	507	5136	272	335	607	4529
January	31	0,5	4396	578	546	5520	306	335	640	4879
February	28	2,4	3350	541	445	4336	413	302	716	3620
March	31	7,6	2166	575	347	3088	638	335	972	2116
April	15	10,4	607	336	130	1073	398	162	560	517

Table 25. Winter thermal need

Where:

$\theta_{e,m}$ month-average outdoor temperature

$Q_{h,tr}$ Energy lost by transmission

$Q_{h,r}$ Energy lost by extraflux

$Q_{h,ve}$ Energy lost by ventilation, calculated with 0.3 vol/h

$Q_{h,ht}$ Total energy lost

$Q_{sol,w}$ energy provided by sun

Q_{int} heat energy provided by the usage of the house

Q_{gn} total energy provided by sources different from heating plant and heating devices.

$Q_{h,nd}$ total energy needs

The results at the end of the winter are:

Energy lost	kWh	Energy intake	kWh
Qh,tr	18468	Qsol,w	2600
Qh,r	3280	Qint	1976
Qh,ve	2502		
Total		**Total**	
Qh,ht	**24249**	**Qgn**	**4576**

Energy balance	
Qh,nd	**19679 kWh**
Specific energy need	**144.07 kWh/m^2**
Specific energy need	**33.04 kWh/m^3**

The power required to heat the house when there aren't positive contributions and the outside temperature is at its coldest, is 12.37 kW (10.57 kW transmission losses and 1.8 kW ventilation losses)

Summer needs

The hot season starts on 18th April and it ends on 8 October

Month	n. of days	θe,m [°C]	Qc,tr [kWh]	Qc,r [kWh]	Qc,ve [kWh]	Qc,ht [kWh]	Qsol,w [kWh]	Qint [kWh]	Qgn [kWh]	Qc,nd [kWh]
April	13	13,0	878	326	152	1356	345	140	486	0
May	31	17,3	850	721	243	1814	996	335	1331	11
June	30	21,4	-328	775	125	572	1099	324	1423	851
July	31	22,9	-802	908	87	193	1186	335	1521	1328
August	31	21,9	-374	653	115	394	1020	335	1355	962
September	30	18,4	770	584	206	1560	748	324	1072	5
October	8	14,0	579	157	87	823	133	86	219	0

Table 26. Summer thermal need

The results at the end of the hot season are:

Energy lost	kWh	Energy intake	kWh
Qh,tr	1573	Qsol,w	5528
Qh,r	4124	Qint	1879
Qh,ve	1014		
Total		**Total**	
Qh,ht	**6712**	**Qgn**	**7404**

Energy balance	
Qh,nd	**3156 kWh**
Specific energy need	**23.10 kWh/m^2**
Specific energy need	**5.30 kWh/m^3**

APE certificate

EdilClima has a tool that gives the opportunity to calculate the APE even if the existing building is without any plant, that is the case. The software simulates the most common plant (natural gas boiler).

The existing house is in **D class** with **EP$_{gl,nren}$** equal to **224.64 kWh/m^{2}a**

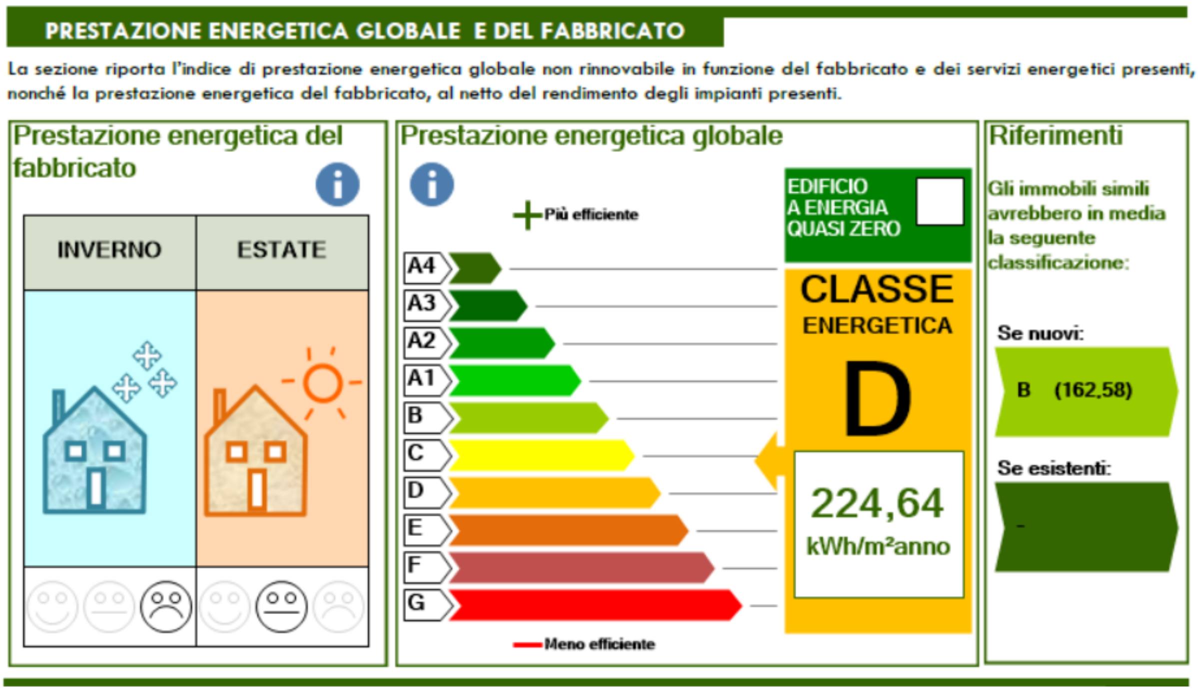


Figure 25. APE certificate for the current building

Renovation scenarios

In this chapter the different elements of the house will be analyzed under the energy point of view and compared together, keeping in mind the legislative constraints and also the economic factor.

At the end of the analysis some elements of will be optimized and other will be reduced to few options equally worthy.

To a better clarity of the work, it is underlined that only the residential part will undergo renovations, not all the entire building.

Windows optimization

The initial windows, as seen in the previous chapter, have a really high thermal transmittance (4.9 W/m^{2}K) and so they have the following terrific performance.

Cold season

Description	U [W/m²K]	Area Tot [m²]	Qh,tr [kWh]	Qh,r [kWh]	Qsol,k [kWh]
Window 100 x 220	4,900	6,60	2151	228	487
Window 100 x 150	4,900	13,50	4399	466	1683
Window 60 x 150	4,900	0,90	293	31	185
Window 210 x 120	4,900	2,52	821	87	245
Total			**7764**	**811**	**2600**
Balance	**-5975 kWh**				

Table 27. Energy balance through windows

Hot season

Description	U [W/m²K]	Area Tot [m²]	Qh,tr [kWh]	Qh,r [kWh]	Qsol,k [kWh]
Window 100 x 220	4,900	6,60	872	291	1428
Window 100 x 150	4,900	13,50	1784	594	3171
Window 60 x 150	4,900	0,90	119	40	249
Window 210 x 120	4,900	2,52	333	111	680
Total			**3108**	**1035**	**5528**
Balance	**+1385 kWh**				

Table 28. Energy balance through windows

Legislative constrains

As seen in the first chapter, the national law requires the installation of a window with thermal transmittance equal or below 1.4 W/m^{2}K. The regional law has a weaker standard so the national one is the one to follow.

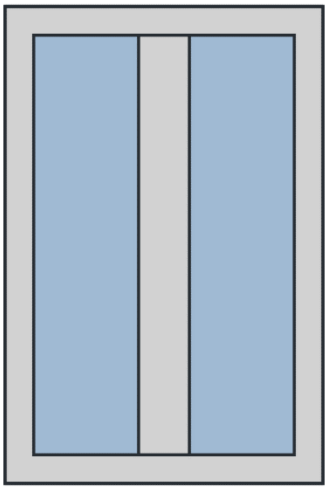
Anyway on the market the most available windows have a transmittance of 1.3 W/m^{2}K, thus it is the first choice.

Moreover, the DM requisiti minimi[6], also demands that the sun light transmittance of the window combined with adjustable shadowing systems (as a curtain) must be equal or below 0.35. This means that a shadowing system must be installed.

It is chosen a Venetian blind installed outside the window, reducing the sun exposure of 85%.

The new windows are as described below. Since all the windows have the same feature, only one example is attached.

Description: ***Window 100 x 150***



Feature			
Thermal transmittance	U_w	***1.300***	W/m^{2}K
Glass transmittance	U_g	***1.100***	W/m^{2}K
Solar contribute and shadowing			
Emissivity	ε	***0,837***	-
Solar transmittance factor	$g_{gl,n}$	***0,670***	-
Shadow factor(winter)	$f_{c\ inv}$	***1.00***	-
Shadow factor (summer)	$f_{c\ est}$	***0.15***	-
Size			
Width		***100,0***	cm
Height		***150,0***	cm
Frame			
Area	A_w	***1,500***	m^2
Glass area	A_g	***0,884***	m^2
Frame area	A_f	***0,616***	m^2
Shape factor	F_f	***0,59***	-
Glass perimeter	L_g	***6,620***	m
Frame perimeter	L_f	***5,000***	m
Thermal bridge			
Linear thermal transmittance	Ψ	***0,278***	W/mK
Perimeter		***5,00***	m

The results are in the tables below.

Cold season

Description	U [W/m²K]	Area Tot [m²]	Qh,tr [kWh]	Qh,r [kWh]	Qsol,k [kWh]
Window 100 x 220	1,300	6,60	571	60	371
Window 100 x 150	1,300	13,50	1167	124	1285
Window 60 x 150	1,300	0,90	78	8	141
Window 210 x 120	1,300	2,52	218	23	187
Total			**2033**	**215**	**1984**
Balance	**-264 kWh**				

Table 29. Energy balance through windows

Hot season

Description	U [W/m²K]	Area Tot [m²]	Qh,tr [kWh]	Qh,r [kWh]	Qsol,k [kWh]
Window 100 x 220	1,300	6,60	166	66	665
Window 100 x 150	1,300	13,50	340	134	1151
Window 60 x 150	1,300	0,90	23	9	66
Window 210 x 120	1,300	2,52	63	25	324
Total			**592**	**234**	**2206**
Balance	**+1380 kWh**				

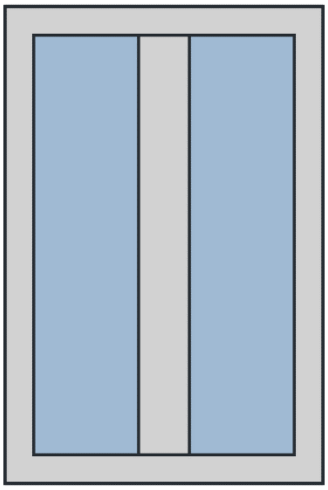
Table 30. Energy balance through windows

Optimization

In order to optimize the window a new configuration is tried. The idea behind is that better windows with a triple glazed have better insulation performance but at the same time they reduce the solar free energy that comes inside. So a possible balance can be obtained installing double-glazed windows(U=1.3 W/m²K) on the south and South-West sides and a triple-glazed ones on the other facades.

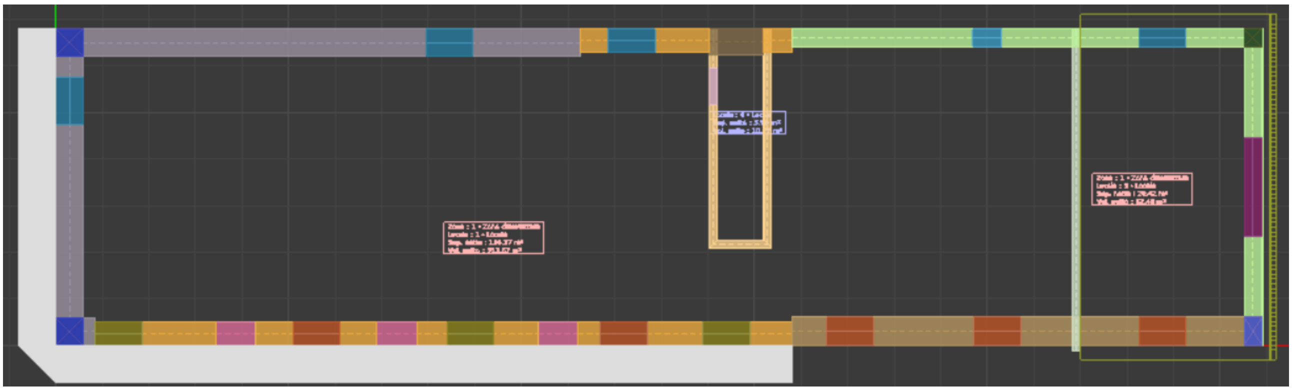
The features of a triple glazed window are the following.

Description: ***Window 100 x 150***



Feature			
Thermal transmittance	U_w	**0.800**	W/m²K
Glass transmittance	U_g	**0.600**	W/m²K
Solar contribute and shadowing			
Emissivity	ε	**0,837**	-
Solar transmittance factor	$g_{gl,n}$	**0,50**	-
Shadow factor(winter)	$f_{c\ inv}$	**1.00**	-
Shadow factor (summer)	$f_{c\ est}$	**0.15**	-
Size			
Width		**100,0**	cm
Height		**150,0**	cm
Frame			
Area	A_w	**1,500**	m²
Glass area	A_g	**0,884**	m²
Frame area	A_f	**0,616**	m²
Shape factor	F_f	**0,59**	-
Glass perimeter	L_g	**6,620**	m
Frame perimeter	L_f	**5,000**	m
Thermal bridge			
Linear thermal transmittance	Ψ	**0,278**	W/mK
Perimeter		**5,00**	m

The orientation is the following.



Color	Description
	Double glazed windows
	Triple glazed windows
	Triple glazed windows
	Triple glazed windows

Figure 26. Colored planimetry to show the position of the various windows

The results are really good.

Cold season

Description	U [W/m²K]	Area Tot [m²]	Qh,tr [kWh]	Qh,r [kWh]	Qsol,k [kWh]
Window 100 x 220	0,800	6,60	351	37	270
Window 100 x 150	0,800	7,50	399	42	294
Window 60 x 150	1,300	0,90	78	8	141
Window 210 x 120	0,800	2,52	134	14	136
Window 100x150 1.3	1,300	6,00	519	55	881
Total			**1481**	**157**	**1723**
Balance	**+85 kWh**				

Table 31. Energy balance through windows

Hot season

Description	U [W/m²K]	Area Tot [m²]	Qh,tr [kWh]	Qh,r [kWh]	Qsol,k [kWh]
Window 100 x 220	0,800	6,60	102	40	484
Window 100 x 150	0,800	7,50	116	46	527
Window 60 x 150	1,300	0,90	23	9	66
Window 210 x 120	0,800	2,52	39	15	235
Window 100x150 1.3	1,300	6,00	151	60	426
Total			**431**	**170**	**1739**
Balance	**+1138 kWh**				

Table 32. Energy balance through windows

One last hypothesis must be verified: if installing only triple-glazed windows can reach better results.

Comparing two and three glass windows on the most irradiated side (on the same side) it is clear that the difference is negligible. So because triple glazed window are more expensive, they are not installed where not necessary.

Winter

Description	U [W/m²K]	Area Tot [m²]	Qh,tr [kWh]	Qh,r [kWh]	Qsol,k [kWh]	Balance [kWh]
Double glazed window	1,300	1.50	130	14	220	+76
Triple glazed window	0.800	1.50	80	8.4	164	+75.6

Table 33. Comparison between double and triple glazed window

Summer

Description	U [W/m²K]	Area Tot [m²]	Qh,tr [kWh]	Qh,r [kWh]	Qsol,k [kWh]	Balance [kWh]
Double glazed window	1,300	1.50	37.8	15	106.5	+53.7
Triple glazed window	0.800	1.5	23.2	9.2	79.5	+47.1

Table 34. Comparison between double and triple glazed window

Final comparison

To complete the optimization of windows, the overall results are compared.

Double glazed windows

Hot season

Energy balance	Existing case	Double glazed	Variation
Qh,nd	3156 kWh	2507 kWh	-20.56%
Specific energy need	23.10 kWh/m²	18.35 kWh/m²	
Specific energy need	5.30 kWh/m³	4.21 kWh/m³	

Cold season

Energy balance	Existing case	Double glazed	Variation
Qh,nd	19679 kWh	14068 kWh	-28.5%
Specific energy need	144.07 kWh/m²	102.99 kWh/m²	
Specific energy need	33.04 kWh/m³	23.62 kWh/m³	

Optimized

Hot season

Energy balance	Existing case	Optimized	Variation
Qh,nd	3156 kWh	2299 kWh	-27.2%
Specific energy need	23.10 kWh/m²	16.83 kWh/m²	
Specific energy need	5.30 kWh/m³	3.89 kWh/m³	

Cold season

Energy balance	Existing case	Optimized	Variation
Qh,nd	19679 kWh	13715 kWh	-30.3%
Specific energy need	144.07 kWh/m²	100.41 kWh/m²	
Specific energy need	33.04 kWh/m³	23.03 kWh/m³	

With a well-designed approach, only changing windows it is possible to make jump of two classes up to **B class**

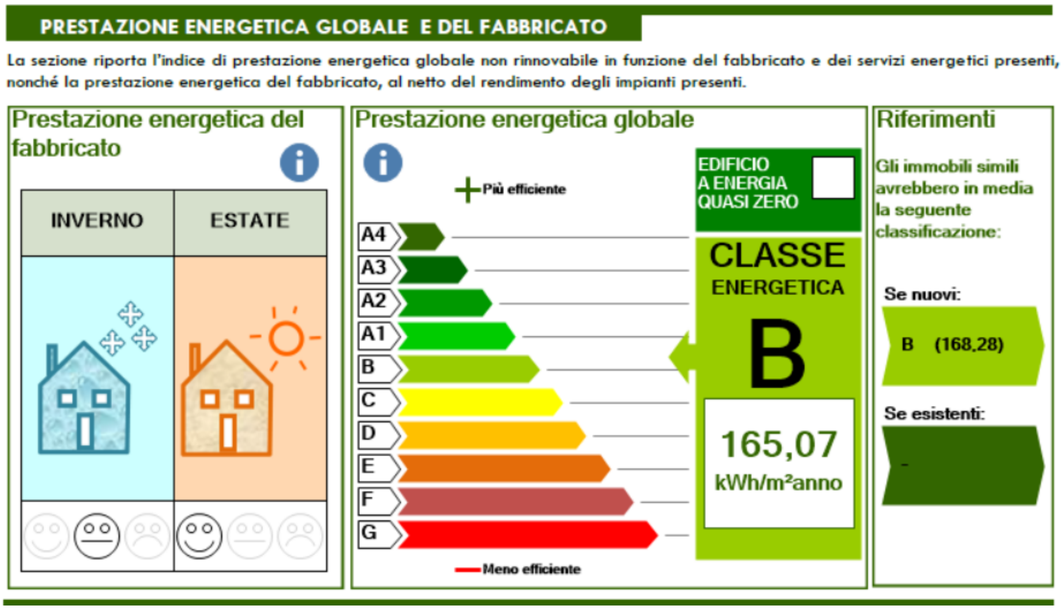


Figure 27. APE certificate with insulated windows

Wall insulation

The legal minimum

The first simulation for the wall insulation is the one that respects all the rules, that are here summarized.

Description	National requirements	Piedmont requirements.	Final
Vertical structures	0.26 W/m^{2}K	0.325 W/m^{2}K	0.26 W/m^{2}K
Roof or ceiling	0.22 W/m^{2}K	0.30 W/m^{2}K	0.22 W/m^{2}K
Floor	0.26 W/m^{2}K	0.30 W/m^{2}K	0.26 W/m^{2}K
Windows	1.4 W/m^{2}K	1.7 W/m^{2}K	1.4 W/m^{2}K

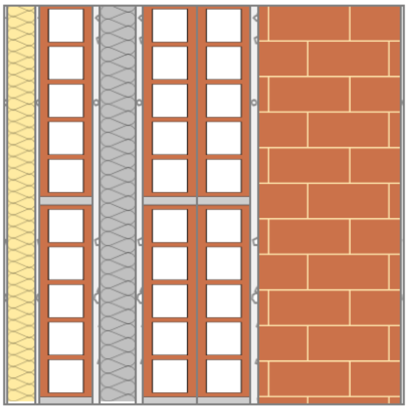
Table 35. Legal minimum thermal transmittance for opaque structures

As a first approach, as insulating material it is used the sintered polystyrene foam EPS whose characteristics are the following: thermal conductivity 0.042 W/mK, density 10-13 kg/m^3. Then, because some walls have humidity problems a polyethylene vapor barrier is also installed.

The walls and the horizontal structure are described in detail below.

Description: *Wall A1 brick*

Thermal transmittance	***0,263***	W/m^2K
Thickness	***560***	mm
Outdoor temperature	***-8,8***	°C
Permeance	***23,824***	$10^{-12} kg/sm^2Pa$
Surface mass (with plaster)	***644***	kg/m^2
Surface mass (without plaster)	***571***	kg/m^2
Periodic transmittance	***0,003***	W/m^2K
Attenuation factor	***0,012***	-
Thermal wave phase shift	***-21,5***	h



Stratigraphy:

N.	Description	s	Cond.	R	M.V.	C.T.	R.V.
1	Gypsum plaster	5,00	0,4000	0,013	1000	1,00	10
2	Synthetic expanded polystyrene in block slabs	40,00	0,0420	0,952	25	1,45	60
3	Lime mortar or lime and cement mortar	5,00	0,9000	0,006	1800	1,00	22
4	6 HOLES 8 (interior wall)	75,00	0,2880	0,260	825	1,00	5
5	Lime mortar or lime and cement mortar	10,00	0,9000	0,011	1800	1,00	22
6	Sintered expanded polystyrene (graphite-like)	50,00	0,0310	1,613	20	1,45	60
7	Lime mortar or lime and cement mortar	10,00	0,9000	0,011	1800	1,00	22
8	21 HOLE 19 (interior wall)	75,00	0,3000	0,250	979	1,00	5
9	21 HOLE 19 (exterior wall)	75,00	0,3150	0,238	979	1,00	5
10	Lime mortar or lime and cement mortar	10,00	0,9000	0,011	1800	1,00	22
11	solid brick	200,00	0,7780	0,257	1800	0,84	5
12	Gypsum plaster	5,00	0,4000	0,013	1000	1,00	10

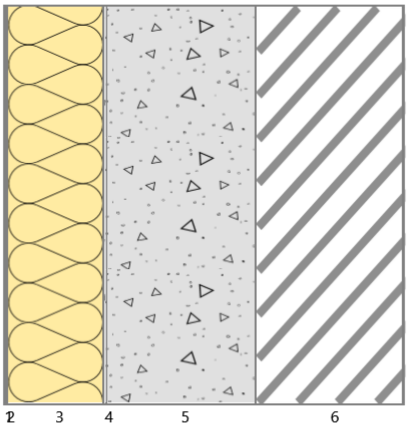
Table 36. Insulated wall stratigraphy

Caption

s	Thickness	mm
Cond.	Thermal conductivity, including any correction coefficients	W/mK
R	Thermal resistance	m^2K/W
M.V.	Mass density	kg/m^3
C.T.	Specific thermal capacity	kJ/kgK
R.V.	Vapor diffusion resistance factor in dry end	-

Description: ***Wall A1 reinforced concrete***

Thermal transmittance	***0,235***	W/m²K
Thickness	***670***	mm
Outdoor temperature	***-8,8***	°C
Permeance	***1,196***	10^{-12}kg/sm²Pa
Surface mass (with plaster)	***1218***	kg/m²
Surface mass (without plaster)	***1205***	kg/m²
Periodic transmittance	***0,010***	W/m²K
Attenuation factor	***0,042***	-
Thermal wave phase shift	***-14,9***	h



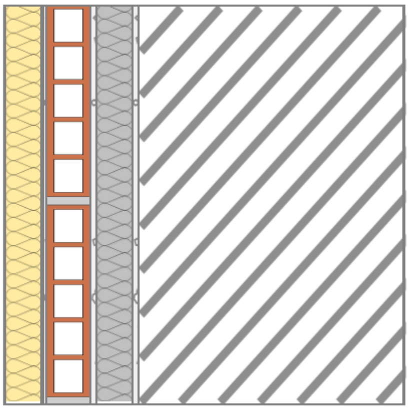
Stratigraphy:

N.	Description	s	Cond.	R	M.V.	C.T.	R.V.
1	Gypsum plaster	*4,00*	*0,4000*	*0,010*	*1000*	*1,00*	*10*
2	Vapor barrier in polyethylene sheets	*1,00*	*0,3300*	*0,003*	*920*	*2,20*	*100000*
3	Synthetic expanded polystyrene in block sheets	*160,00*	*0,0420*	*3,810*	*25*	*1,45*	*60*
4	Lime mortar or lime and cement mortar	*5,00*	*0,9000*	*0,006*	*1800*	*1,00*	*22*
5	Reinforced c.l.s. (1% steel)	*250,00*	*2,3000*	*0,109*	*2300*	*1,00*	*130*
6	Natural stone masonry	*250,00*	*2,3000*	*0,109*	*2500*	*1,00*	*100*

Table 37. Insulated wall stratigraphy

Description: ***Wall A1 stone***

Thermal transmittance	***0,251***	W/m²K
Thickness	***675***	mm
Outdoor temperature	***-8,8***	°C
Permeance	***1,306***	10^{-12}kg/sm²Pa
Surface mass (with plaster)	***1251***	kg/m²
Surface mass (without plaster)	***1202***	kg/m²
Periodic transmittance	***0,002***	W/m²K
Attenuation factor	***0,008***	-
Thermal wave phase shift	***-20,0***	h



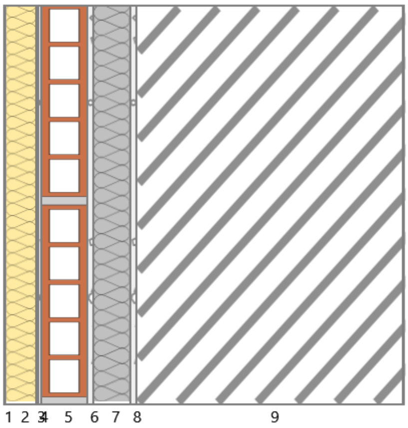
Stratigraphy:

N.	Description	s	Cond.	R	M.V.	C.T.	R.V.
1	Gypsum plaster	*4,00*	*0,4000*	*0,010*	*1000*	*1,00*	*10*
2	Synthetic expanded polystyrene in block sheets	*60,00*	*0,0420*	*1,429*	*25*	*1,45*	*60*
3	Vapor barrier in polyethylene sheets	*1,00*	*0,3300*	*0,003*	*920*	*2,20*	*100000*
4	Lime mortar or lime and cement mortar	*5,00*	*0,9000*	*0,006*	*1800*	*1,00*	*22*
5	21 HOLES 19 (interior wall)	*75,00*	*0,3000*	*0,250*	*979*	*1,00*	*5*
6	Lime mortar or lime and cement mortar	*10,00*	*0,9000*	*0,011*	*1800*	*1,00*	*22*
7	Sintered expanded polystyrene (graphite)	*60,00*	*0,0320*	*1,875*	*15*	*1,45*	*60*
8	Lime mortar or lime and cement mortar	*10,00*	*0,9000*	*0,011*	*1800*	*1,00*	*22*
9	Natural stone masonry	*450,00*	*2,3000*	*0,196*	*2500*	*1,00*	*100*

Table 38. Insulated wall stratigraphy

Description: ***Wall B1***

Thermal transmittance	***0,263***	W/m^{2}K
Thickness	***655***	mm
Outdoor temperature	***-8,8***	°C
Permeance	***1,320***	10^{-12}kg/sm^{2}Pa
Surface mass (with plaster)	***1226***	kg/m^2
Surface mass (without plaster)	***1177***	kg/m^2
Periodic transmittance	***0,002***	W/m^{2}K
Attenuation factor	***0,009***	-
Thermal wave phase shift	***-19,7***	h



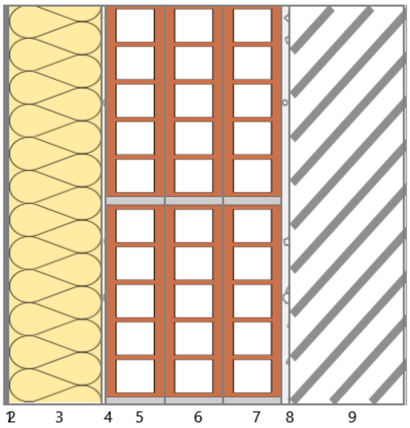
Stratigraphy:

N.	Description	s	Cond.	R	M.V.	C.T.	R.V.
1	Gypsum plaster	*4,00*	*0,4000*	*0,010*	*1000*	*1,00*	*10*
2	Synthetic expanded polystyrene in block sheets	*50,00*	*0,0420*	*1,190*	*25*	*1,45*	*60*
3	Vapor barrier in polyethylene sheets	*1,00*	*0,3300*	*0,003*	*920*	*2,20*	*100000*
4	Lime mortar or lime and cement mortar	*5,00*	*0,9000*	*0,006*	*1800*	*1,00*	*22*
5	21 HOLES 19 (interior wall)	*75,00*	*0,3000*	*0,250*	*979*	*1,00*	*5*
6	Lime mortar or lime and cement mortar	*10,00*	*0,9000*	*0,011*	*1800*	*1,00*	*22*
7	Sintered expanded polystyrene (graphite)	*60,00*	*0,0310*	*1,935*	*20*	*1,45*	*60*
8	Lime mortar or lime and cement mortar	*10,00*	*0,9000*	*0,011*	*1800*	*1,00*	*22*
9	Natural stone masonry	*440,00*	*2,3000*	*0,191*	*2500*	*1,00*	*100*

Table 39. Insulated wall stratigraphy

Description: *Wall D1*

Thermal transmittance	***0,256***	W/m^2K
Thickness	***514***	mm
Outdoor temperature	***-8,8***	°C
Permeance	***3,725***	$10^{-12}kg/sm^2Pa$
Surface mass (with plaster)	***630***	kg/m^2
Surface mass (without plaster)	***599***	kg/m^2
Periodic transmittance	***0,013***	W/m^2K
Attenuation factor	***0,051***	-
Thermal wave phase shift	***-16,2***	h



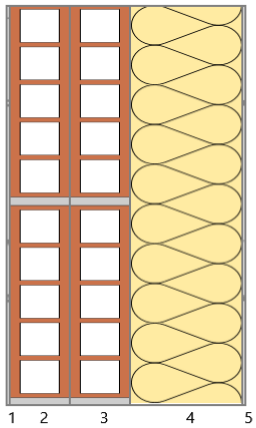
Stratigraphy:

N.	Description	s	Cond.	R	M.V.	C.T.	R.V.
1	Gypsum plaster	*4,00*	*0,4000*	*0,010*	*1000*	*1,00*	*10*
2	Vapor barrier in polyethylene sheets	*0,30*	*0,3300*	*0,001*	*920*	*2,20*	*100000*
3	Synthetic expanded polystyrene in block sheets	*120,00*	*0,0420*	*2,857*	*25*	*1,45*	*60*
4	Lime mortar or lime and cement mortar	*5,00*	*0,9000*	*0,006*	*1800*	*1,00*	*22*
5	21 HOLES 19 (interior wall)	*75,00*	*0,3000*	*0,250*	*979*	*1,00*	*5*
6	21 HOLE 19 (interior wall)	*75,00*	*0,3000*	*0,250*	*979*	*1,00*	*5*
7	21 HOLE 19 (interior wall)	*75,00*	*0,3000*	*0,250*	*979*	*1,00*	*5*
8	Lime mortar or lime and cement mortar	*10,00*	*0,9000*	*0,011*	*1800*	*1,00*	*22*
9	Natural stone masonry	*150,00*	*2,3000*	*0,065*	*2500*	*1,00*	*100*

Table 40. Insulated wall stratigraphy

Description: ***internal wall***

Thermal transmittance	***0,241***	W/m^2K
Thickness	***300***	mm
Outdoor temperature	***-0,2***	°C
Permeance	***21,622***	$10^{-12}kg/sm^2Pa$
Surface mass (with plaster)	***156***	kg/m^2
Surface mass (without plaster)	***140***	kg/m^2
Periodic transmittance	***0,069***	W/m^2K
Attenuation factor	***0,287***	-
Thermal wave phase shift	***-8,6***	h



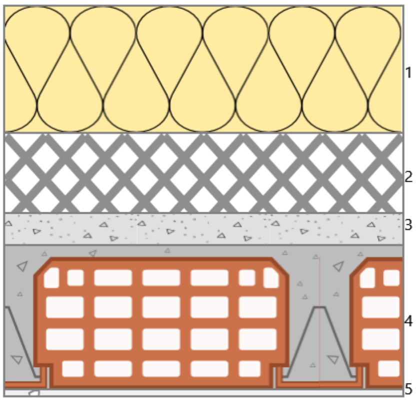
Stratigraphy:

N.	Description	s	Cond.	R	M.V.	C.T.	R.V.
1	Lime and sand plaster	*5,00*	*0,8000*	*0,006*	*1600*	*1,00*	*10*
2	6 HOLES 6 (interior wall)	*75,00*	*0,2750*	*0,273*	*911*	*1,00*	*5*
3	6 HOLES 6 (interior wall)	*75,00*	*0,2750*	*0,273*	*911*	*1,00*	*5*
4	Synthetic expanded polystyrene in slabs from blocks	*140,00*	*0,0420*	*3,333*	*25*	*1,45*	*60*
5	Lime and sand plaster	*5,00*	*0,8000*	*0,006*	*1600*	*1,00*	*10*

Table 41. Insulated wall stratigraphy

Description: ***Ceiling first floor***

Thermal transmittance	***0,220***	W/m^2K
Thickness	***490***	mm
Outdoor temperature	***-5,0***	°C
Permeance	***11,547***	$10^{-12}kg/sm^2Pa$
Surface mass (with plaster)	***437***	kg/m^2
Surface mass (without plaster)	***421***	kg/m^2
Periodic transmittance	***0,018***	W/m^2K
Attenuation factor	***0,081***	-
Thermal wave phase shift	***-12,5***	h

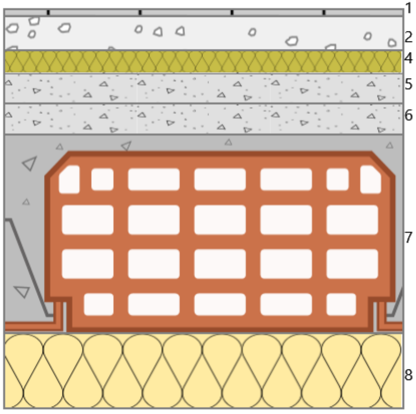


Stratigraphy:

N.	Description	s	Cond.	R	M.V.	C.T.	R.V.
1	Synthetic expanded polystyrene in slabs from blocks	*160,00*	*0,0420*	*3,810*	*25*	*1,45*	*60*
2	Predosed Leca lightweight concrete	*100,00*	*0,4700*	*0,213*	*1500*	*1,00*	*8*
3	Reinforced c.l.s. (2% steel)	*40,00*	*2,5000*	*0,016*	*2400*	*1,00*	*130*
4	Attic block	*180,00*	*0,6000*	*0,300*	*950*	*0,84*	*9*
5	Lime and sand plaster	*10,00*	*0,8000*	*0,013*	*1600*	*1,00*	*10*

Table 42. Insulated wall stratigraphy

Description: ***floor of first floor***



Thermal transmittance	***0,249***	W/m^2K
Thickness	***525***	mm
Outdoor temperature	***-6,4***	°C
Permeance	***0,002***	$10^{-12}kg/sm^2Pa$
Surface mass (with plaster)	***596***	kg/m^2
Surface mass (without plaster)	***596***	kg/m^2
Periodic transmittance	***0,004***	W/m^2K
Attenuation factor	***0,015***	-
Thermal wave phase shift	***-15,9***	h

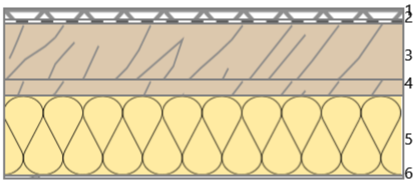
Stratigraphy:

N.	Description	s	Cond.	R	M.V.	C.T.	R.V.
1	Ceramic tiles (tiles)	*10,00*	*1,3000*	*0,008*	*2300*	*0,84*	*9999999*
2	Self-levelling screed mix	*45,00*	*1,4000*	*0,032*	*1950*	*1,00*	*100*
3	Panel pipe - H30 (density 25 kg/mc)	*0,00*	-	-	-	-	-
4	Expanded polystyrene for CLASSIC FLOOR - PLAN FLOOR	*30,00*	*0,0350*	*0,857*	*25*	*1,21*	*70*
5	Concrete distribution screed with mesh	*40,00*	*1,4900*	*0,027*	*2200*	*0,88*	*70*
6	Reinforced c.l.s. (2% steel)	*40,00*	*2,5000*	*0,016*	*2400*	*1,00*	*130*
7	Floor block	*260,00*	*0,7430*	*0,350*	*1146*	*0,84*	*9*
8	Synthetic expanded polystyrene in block slabs	*100,00*	*0,0420*	*2,381*	*25*	*1,45*	*60*

Table 43. Insulated wall stratigraphy

Description: ***one pitch roof***

Thermal transmittance	***0,222***	W/m²K
Thickness	***214***	mm
Outdoor temperature	***-8,8***	°C
Permeance	***0,911***	10^{-12}kg/sm²Pa
Surface mass (with plaster)	***63***	kg/m²
Surface mass (without plaster)	***58***	kg/m²
Periodic transmittance	***0,094***	W/m²K
Attenuation factor	***0,425***	-
Thermal wave phase shift	***-7,4***	h



Stratigraphy:

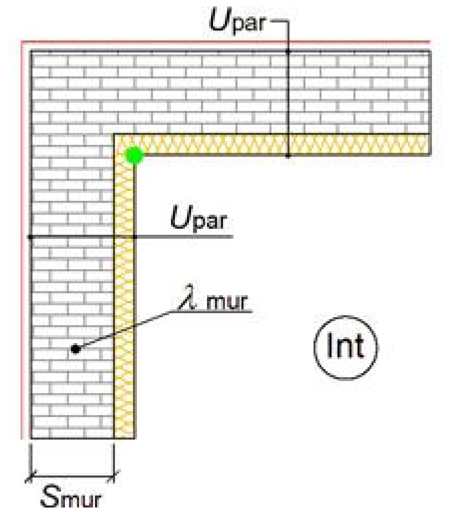
N.	Description	s	Cond.	R	M.V.	C.T.	R.V.
1	Terracotta tiles	*15,00*	*1,0000*	*0,015*	*2000*	*0,80*	*40*
2	Bitumen vapor barrier felt/foil	*4,00*	*0,2300*	*0,017*	*1100*	*1,00*	*50000*
3	Wood fiber	*70,00*	*0,0400*	*1,750*	*170*	*2,00*	*5*
4	Spruce wood flow perpend. to fibers	*20,00*	*0,1200*	*0,167*	*450*	*1,60*	*625*
5	Synthetic expanded polystyrene in slabs from blocks	*100,00*	*0,0420*	*2,381*	*25*	*1,45*	*60*
6	Gypsum plaster	*5,00*	*0,4000*	*0,013*	*1000*	*1,00*	*10*

Table 44. Insulated wall stratigraphy

Only one thermal bridge for each type is reported as example.

Description: ***Corner between walls (wall B1 -wall B1)***

Type	***Wall corner***	
Linear thermal transmittance for calculations	***-0,158***	W/mK
Reference linear thermal transmittance	***-0,315***	W/mK
Temperature factor frsi	***0,851***	-
Reference	***UNI EN ISO 14683 e UNI EN ISO 10211***	



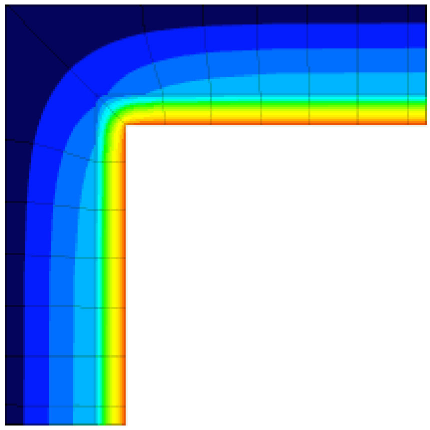
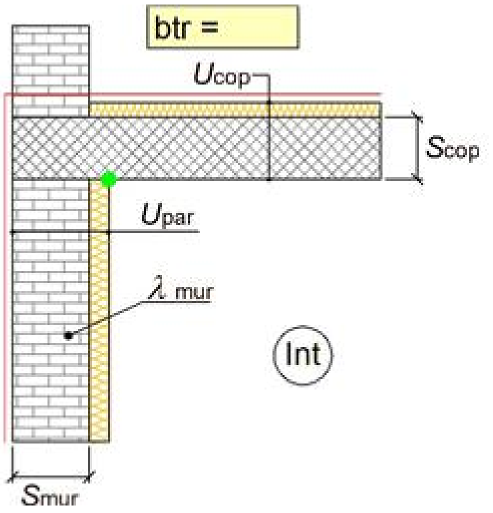


Figure 28. Thermal bridge at corner between walls

Description: ***Wall-ceiling intersection***

Type	***Wall ceiling intersection***	
Linear thermal transmittance for calculations	***0,093***	W/mK
Reference linear thermal transmittance	***0,186***	W/mK
Temperature factor frsi	***0,571***	-
Reference	***UNI EN ISO 14683 e UNI EN ISO 10211***	



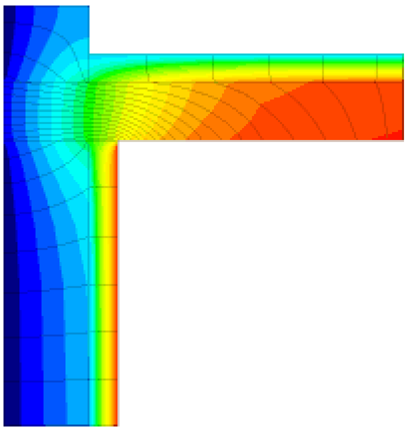
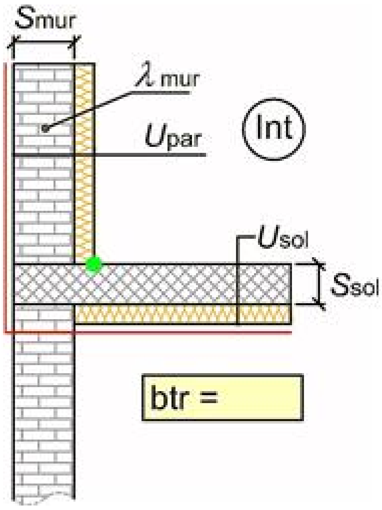


Figure 29. Thermal bridge at wall-cieling intersection

Description: ***Wall-floor intersection***

Type	***GF - Parete - Solaio rialzato***	
Linear thermal transmittance for calculations	***0,106***	W/mK
Reference linear thermal transmittance	***0,212***	W/mK
Temperature factor frsi	***0,554***	-
Reference	***UNI EN ISO 14683 e UNI EN ISO 10211***	



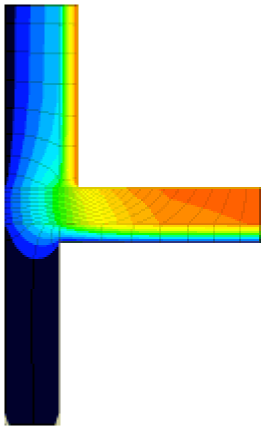
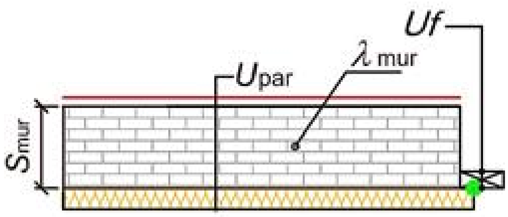


Figure 30. Thermal bridge at wall-floor intersection

Description: ***wall- window frame***

Type	***wall- window frame***	
Linear thermal transmittance for calculations	***0,013***	W/mK
Reference linear thermal transmittance	***0,013***	W/mK
Temperature factor frsi	***0,830***	-
Reference	***UNI EN ISO 14683 e UNI EN ISO 10211***	



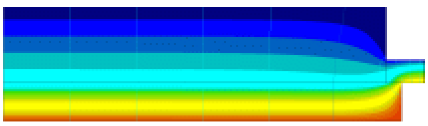


Figure 31. Window frame thermal bridge

Results

Existing building - cold season

Description	U [W/m²K]	Area Tot [m²]	Qh,tr [kWh]	Qh,r [kWh]	Qsol,k [kWh]
Wall B1	0,384	62,30	1590	181	401
Wall A1 brick	0,350	44,03	1024	117	143
Wall D1	0,968	52,24	3363	383	720
Wall A1 concrete	2,357	8,82	1383	157	135
Wall A1 stone	0,392	30,81	804	91	79
Internal wall	1,204	33,71	958	-	-
Floor	0,614	171,58	5819	-	-
Ceiling	1,349	144,41	6907	-	-
One-pitch roof	0,472	27,58	865	197	195
Total			**22713**	**1126**	**1673**
Thermal bridges	**+8068 kWh**				
Balance	**-14098 kWh**				

Table 45. Energy through opaque structures

Legal minimum case - cold season

Description	U [W/m²K]	Area Tot [m²]	Qh,tr [kWh]	Qh,r [kWh]	Qsol,k [kWh]
Wall B1	0,260	66,65	1164	132	294
Wall A1 brick	0,260	48,18	835	95	118
Wall D1	0,256	55,66	949	108	203
Wall A1 concrete	0,235	9,39	147	17	14
Wall A1 stone	0,251	32,97	549	63	54
Internal wall	0,241	36,03	406	-	-
Floor	0,249	171,84	2609	-	-
Ceiling	0,220	144,67	1839	-	-
One-pitch roof	0,222	27,58	406	92	92
Total			**8904**	**507**	**775**
Thermal bridges	**-825 kWh**				
Balance	**-9461 kWh**				
Energy saving	**4637 kWh**			**-32.8%**	

Table 46. Energy through opaque structures

A problem with the renovation is that the law says that the minimum height for the room is 2.70m and it is possible to reduce it to 2.60m for energetic renovations[6] (as the one of this project). The height of the room is 2.70 and some space is occupied by the heating floor. So it is not possible to insulate the horizontal structures from the inside and this enhances the thermal bridges. It is neither possible insulate all the living area from the outside for preserving the distinctive facades made by stones. Moreover, insulating by the outside, would have the same problems with thermal bridges because to avoid them it would be necessary to cover also the non-lived areas (garage and attic). If the distance between the floor and the ceiling were bigger, it would be possible to set near to zero the thermal bridges contribute and saving 800 kWh.

Case 2: 0.20 W/m2K

A second case of insulation is done trying to set the transmittance of the structures at 0.20 W/m^{2}K.

Description	U [W/m²K]	Area Tot [m²]	Qh,tr [kWh]	Qh,r [kWh]	Qsol,k [kWh]
Wall B1	0,200	68,54	912		104
Wall A1 brick	0,190	49,98	631		72
Wall D1	0,195	57,25	741		84
Wall A1 concrete	0,192	9,66	124		14
Wall A1 stone	0,200	33,94	452		51
Internal wall	0,195	37,04	352		-
Floor	0,192	171,93	2050		-
ceiling	0,199	144,76	1686		-
One-pitch roof	0,200	27,58	368		84
Total			**7395**	**409**	**617**
Thermal bridges	**-982 kWh**				
Balance	**-8169 kWh**				
Energy saving	**5929 kWh**			**-42.0%**	

Table 47. Energy through opaque structures

Case 3: Passive house reference

The third scenario tries the transmittance value allowed by the Passive house Standard[24]: 0.15W/m²K.

Description	U [W/m²K]	Area Tot [m²]	Qh,tr [kWh]	Qh,r [kWh]	Qsol,k [kWh]
Wall B1	0,145	71,26	686	78	173
Wall A1 brick	0,149	52,56	522	59	74
Wall D1	0,147	59,77	584	66	125
Wall A1 concrete	0,151	10,02	101	11	10
Wall A1 stone	0,145	35,43	342	39	33
Internal wall	0,153	38,49	296	-	-
Floor	0,146	172,05	1577	-	-
ceiling	0,149	144,88	1306	-	-
One-pitch roof	0,145	27,58	266	61	60
Total			**5762**	**315**	**475**
Thermal bridges	**-1018 kWh**				
Balance	**-5602 kWh**				
Energy saving	**8496 kWh**			**-60.2%**	

Table 48. Energy through opaque structures

Final comparison

To compare only the insulation of the opaque building components, the windows installed are the same (optimized windows case)

Cold season				
Energy balance	**Existing case**	**Legal minimum**	**Case 0.20**	**Case 0.15**
Qh,nd	**13715 kWh**	**9497 kWh**	**8069 kWh**	**6553 kWh**
Specific energy need	**100.41 kWh/m²**	**72.22 kWh/m²**	**63.37 kWh/m²**	**53.43 kWh/m²**
Specific energy need	**23.03 kWh/m³**	**14.80 kWh/m³**	**12.37 kWh/m³**	**9.67 kWh/m²**

Hot season				
Energy balance	**Existing case**	**Legal minimum**	**Case 0.20**	**Case 0.15**
Qh,nd	**2299 kWh**	**1383 kWh**	**1445 kWh**	**1409 kWh**
Specific energy need	**16.83 kWh/m²**	**10.52 kWh/m²**	**11.35 kWh/m²**	**11.48 kWh/m²**
Specific energy need	**3.89 kWh/m³**	**2.15 kWh/m³**	**2.22 kWh/m³**	**2.08 kWh/m³**

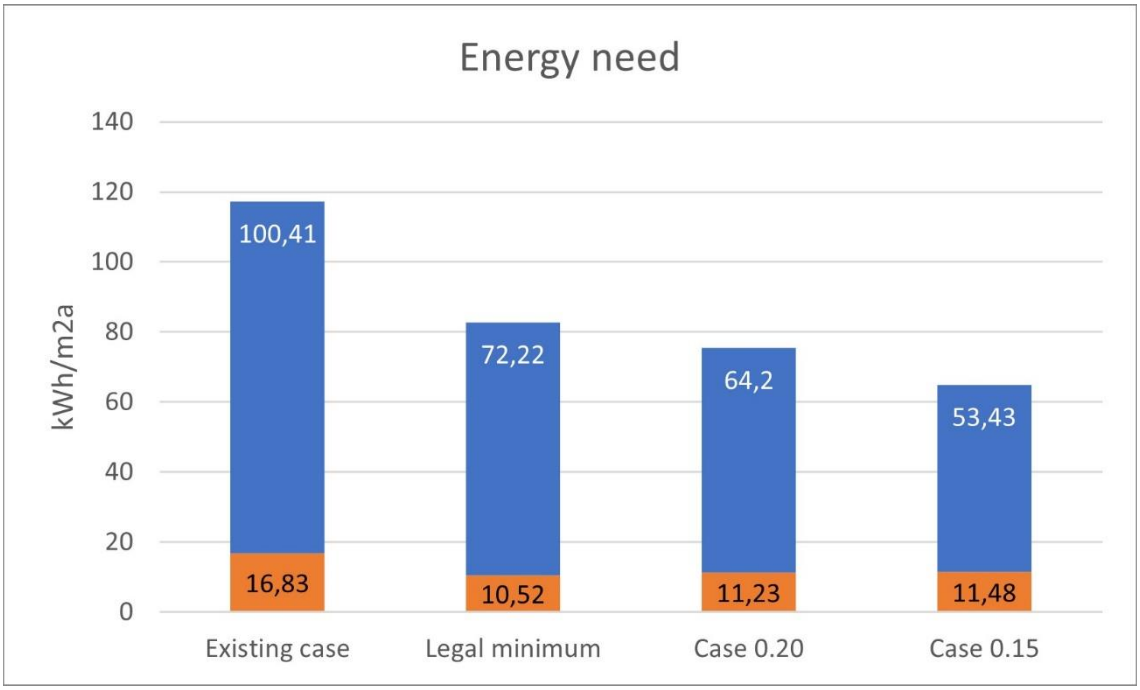


Figure 32. Thermal need comparison among various insulation scenarios

The Passive House standard

The base idea for the Passive House is a building so energetic efficient that doesn't require a large heating or cooling system; most of the heat required is provided by the users with their body heat, living and using hardware. In Germany was born the Passive House Institute and set the requirements[24] that a house must have to be passive. The maximum energy need for a house to be passive is 15 kWh/m^2a for the winter and the same amount for the summer.

Unfortunately, the building under study cannot reach the passive standard, the possible reasons will be discussed after a quick comparison with a real passive house to underline the critical problems.

The reference example is from a research[25] published by Università degli Studi di Firenze and is a house built in Vipiteno (BZ).

	Passive house	This study case
Location	Vipiteno (BZ)	Cumiana (TO)
Degree Days	3959	2829
Global solar irradiance	1270 kWh/m^2a	1384 kWh/m^2a
Wall transmittance	0.138 W/m^2K	0.147 W/m^2K
Ceiling transmittance	0.128 W/m^2K	0.149 W/m^2K
Windows transmittance	0.85 W/m^2K	0.80 W/m^2K
Winter energy need	**10 kWh/m^2a**	**53 kWh/m^2a**

As shown in the table, the differences between the passive house are really small, the passive house have a slightly better wall insulation but worst windows. The most significative difference is the number of heating degree days that is strongly in favor for the house studied in this thesis.
However the final results are not even comparable, the passive house requires a fifth of the energy.

It is clear that the house used for this thesis hasn't the potential to become a passive house.

The building has many limitations:

- Problem with thermal bridges (as discussed in the previous sections)

- Bad orientation of windows, the transparent surface on northern and eastern facades is higher than on the best sun exposed sides.
- Only one lived floor, apartments in the middle of one building reduce the dispersive surface excluding the floor and the ceiling. The reference passive house has three livable floors and so a better ratio between the floor area and the dispersive area.

Plants

The work seen in the previous chapters is useful to save energy in a passive way because it is focused on reducing energy losses. Studying the various plants of the house instead helps saving energy in an active way, increasing the global efficiency. To save energy and to keep a high level of comfort, the most innovative technologies will be investigated such as solar technologies, the best class of the heat pump or the heat recuperator.

The first part of the chapter will study the plants that provide or remove (in summer) the heat. Only after having their consumption will be possible to do the sizing of the power generation plant.

Radiant floor heating

To heat the house the best choice is the radiative floor, because it has several advantages compared to the traditional system with radiators.
The first advantage is that the radiative floor requires an intake water temperature much lower than the radiators, the first one works with water at 35°C and the second one at 75°C. This also allows to use the heat pump to generate heat instead of the natural gas boiler, in fact usually the maximum temperature for a heat pump is around 60°C, also the efficiency of this system is higher the lower the water temperature.
A second reason to prefer the radiant floor is that it heats up the house evenly increasing the comfort level; on the other hand the radiators creates hot spots making some areas of room hot and others cold, then usually the radiators are under the windows and this position significantly increases the heat losses due to a higher temperature gradient.

Lastly, the radiant floor can also be used to cool down the house and this method is the one adopted.

Heat pump

A heat pump is a machine that uses electricity to generate work to absorb heat from the cold environment and give it off to the hot environment. The useful heat generated is much higher than the electrical energy used.

As many other common energivorous devices, heat pump have their own energy classification[26] to inform the users of the best technologies on the market.

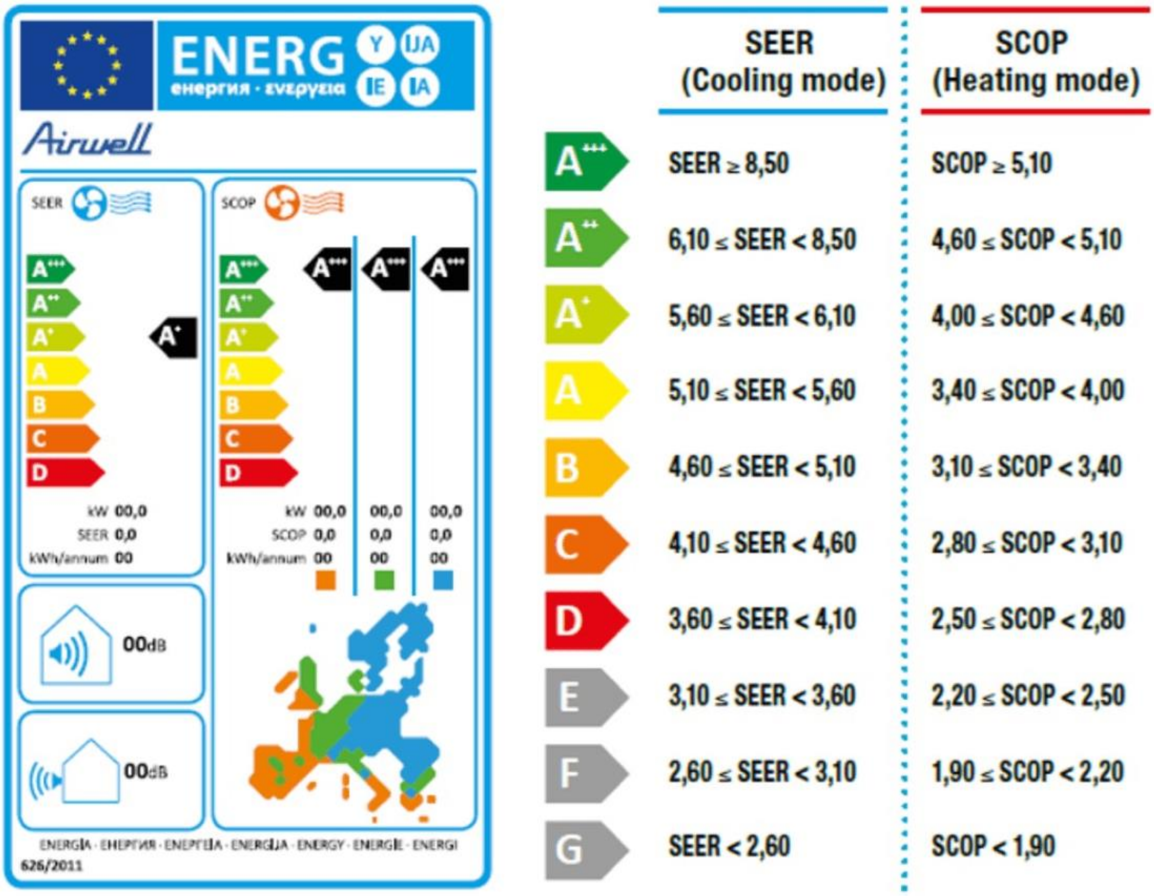


Figure 33. Energy tag for heat pumps

The same heat pump can have different classification between heating and cooling mode.

A heat pump can also be used to generate domestic hot water.

Energy consumption

With reference to the three cases of wall insulation, it is calculated always with EdilClima software, the electrical consumption.

Case 1: legal minimum

<u>**Heating plant**</u>

Thermal needs	**9497 kWh/a**
Electricity consumption	**2456 kWh/a**
Round trip efficiency	**3.87**
<u>More info</u>	
Heat Pump	Ariston NIMBUS 50 S-R32 (7.7kW)
Water temperature	35 °C
Generator output	10207 kWh/a
SCOP	4.15
Plant efficiency	93.0%

<u>**Domestic Hot Water**</u>

Thermal needs	**2107 kWh/a**
Electricity consumption	**686 kWh/a**
Round trip efficiency	**3.07**
<u>More info</u>	
Heat Pump	FERROLI OMNIA M 3.2 (5.5kW)
Generator output	2275 kWh/a
SCOP	3.31
Plant efficiency	92.6%

<u>Cooling plant</u>

Thermal needs	**1383 kWh/a**
Electricity consumption	**331 kWh/a**
Round trip efficiency	**4.17**
<u>More info</u>	
Heat Pump	Ariston NIMBUS 50 S-R32 (7.7kW)
Generator output	1455 kWh/a
SEER	4.40
Plant efficiency	95.0%

Case 2: 0.20 W/m2K

<u>Heating plant</u>

Thermal needs	**8069 kWh/a**
Electricity consumption	**2054 kWh/a**
Round trip efficiency	**3.93**
<u>More info</u>	
Heat Pump	Ariston NIMBUS 50 S-R32 (7.7kW)
Water temperature	35 °C
Generator output	8671 kWh/a
SCOP	4.22
Plant efficiency	93%

<u>Domestic Hot Water</u>

Thermal needs	**2107 kWh/a**
Electricity consumption	**686 kWh/a**
Round trip efficiency	**3.07**
<u>More info</u>	
Heat Pump	FERROLI OMNIA M 3.2 (5.5kW)
Generator output	2275 kWh/a
SCOP	3.31
Plant efficiency	92.6%

<u>Cooling plant</u>

Thermal needs	**1445 kWh/a**
Electricity consumption	**347 kWh/a**
Round trip efficiency	**4.16**
<u>More info</u>	
Heat Pump	Ariston NIMBUS 50 S-R32 (7.7kW)
Generator output	1535 kWh/a
SEER	4.42
Plant efficiency	94.1%

Case 3: 0.15 W/m2K

Heating plant

Thermal needs	**6553 kWh/a**
Electricity consumption	**1595 kWh/a**
Round trip efficiency	**4.10**
More info	
Heat Pump	Ariston NIMBUS 35 S-R32 (6.5kW)
Water temperature	35 °C
Generator output	6842 kWh/a
SCOP	4.29
Plant efficiency	95.8%

Domestic Hot Water

Thermal needs	**2107 kWh/a**
Electricity consumption	**686 kWh/a**
Round trip efficiency	**3.07**
More info	
Heat Pump	FERROLI OMNIA M 3.2 (5.5kW)
Generator output	2275 kWh/a
SCOP	3.31
Plant efficiency	92.6%

Cooling plant

Thermal needs	**1409 kWh/a**
Electricity consumption	**352 kWh/a**
Round trip efficiency	**4.00**
More info	
Heat Pump	Ariston NIMBUS 50 S-R32 (6.5kW)
Generator output	1512 kWh/a
SEER	4.30
Plant efficiency	93.2%

Final Comparison

Total energy consumption

Case 1	Case 2	Case 3
3473 kWh_{el}/year	3087 kWh_{el}/year	2633 kWh_{el}/year
-	-11.1%	-24.2%

Table 49. Thermal energy consumption

Heat recuperator

For health reasons in the house must be a constant air change to breath clear air in the house. The minimum rate is 0.3 vol/h[27].

The heat recuperator is a device that recuperates the heat from the air that flows outside and use it to preheat the fresh air coming in. The efficiency of the best heat recuperator can be higher than 90%, that means that more than 90% of the heat in the indoor air is transferred to the fresh air. The entire aeration plant anyway has some losses reducing the overall efficiency of around 10% and also requires electrical power for the ventilation.

The benefits of installing such a plant must be evaluated.

With a system with a recuperator capacity of 90% and a constant flow rate of 110 m^3/h the results show a good saving. The ventilation plant is not used during the summer because the ventilation losses aren't enough to cover the energy expenditure to run the plant. This hypothesis has been checked and the electricity consumed was higher.

	No recuperator	With recuperator	Electricity saved	Savings
Case 1	2456 kWh_{el}/year	2063 kWh_{el}/year	393 kWh_{el}/year	16.0%
Case 2	2054 kWh_{el}/year	1755 kWh_{el}/year	299 kWh_{el}/year	14.5%
Case 3	1595 kWh_{el}/year	1328 kWh_{el}/year	267 kWh_{el}/year	16.7%

Table 50. Thermal energy consumption with heat recuperator

The installation of the recuperator will be confirmed or not, by the economic analysis.

Energy generation

After having calculated the consumption, it is possible to have some sizes to tailor the Photovoltaic plant, the two options investigated are: covering the consumption or installing the maximum capacity to produce an excess and sell it to the grid.

Roof and PV generation potential

The building has two two-pitch roof and one pitch roof that is north facing so not considered for the PV production. The first two-pitch roof has one pitch with the azimuth of 35° and the tilt angle of 20°, the other has the same azimuth but is tilted by 25°. The total usable area is around 105m^2. With that specification the solar irradiation is 1470 kWh/m^{2}a.

The PV panels installed are the SUNPOWER/Moduli SPR/SPR-2115-WHT, dimension 798x1559 mm, total area 1.24m^2 and useful area 1.13 m^2, power 215 W and 19% of efficiency.

The dimensions of the roof pitches are 1190x446 cm and 1170x463 cm but the last one covers the first over 40cm making the useful size 1150x446. The maximum number of panels is 70, even if the theoretical maximum comparing the area is 84, it is a coverage of 83% so the surface it is properly used.

Self consumption PV plant

The first PV plant has a dimension that at the end of the year, the electricity produced matches the one consumed.

Always referring to the three wall insulation cases the results are. The electricity consumption for all the devices and hardware not used for heating or cooling the house is estimated as 6kWh/day.

	Case 1	**Case 2**	**Case 3**
Thermal needs	**3473 kWh_{el}/year**	**3087 kWh_{el}/year**	**2633 kWh_{el}/year**
User consumption	**2200 kWh_{el}/year**	**2200 kWh_{el}/year**	**2200 kWh_{el}/year**
Total consumption	**5673 kWh_{el}/year**	**5287 kWh_{el}/year**	**4833 kWh_{el}/year**
N. panels	**26**	**24**	**22**
Power	**5.59 kWp**	**5.16 kWp**	**4.73 kWp**

Table 51. PV energy production

In the case the heat recuperator is installed the results are

	Case 1	Case 2	Case 3
Thermal needs	**3080 kWh_{el}/year**	**2788 kWh_{el}/year**	**2366 kWh_{el}/year**
User consumption	**2200 kWh_{el}/year**	**2200 kWh_{el}/year**	**2200 kWh_{el}/year**
Total consumption	**5280 kWh_{el}/year**	**4988 kWh_{el}/year**	**4566 kWh_{el}/year**
N. panels	**24**	**23**	**21**
Power	**5.16 kWp**	**4.95 kWp**	**4.5 kWp**

Table 52. PV energy production in the case with the heat recuperator

Legal minimum renewable generation

For new buildings or the one undergone a complete refurbishment, the decree[29] emitted in 2021 imposes a minimum renewable capacity to cover the 60% of the consumption. The sizes of such PV plants are obviously the 60% of the above calculated cases.

Maximum size PV plant

N. panels	**70**
Power	**15 kWp**
Production	**15500 kWh/year**

Solar thermal collectors

The choice made in this work is to install only PV panels and so the following is the explanation of this decision.

Solar thermal collector are used to generate heat, so they are really useful in winter but in this season their efficiency is lower. The radiant floor uses water at 35°C and so the collector temperature is around 50°C, the outside temperature is around 0°C. A diagram from the documentation of a manufacturer[28] is reported below and it shows the efficiency of the collectors as a function of the temperature difference between the surface of the collector and the air. The efficiency with 50°C of difference is around 55%.

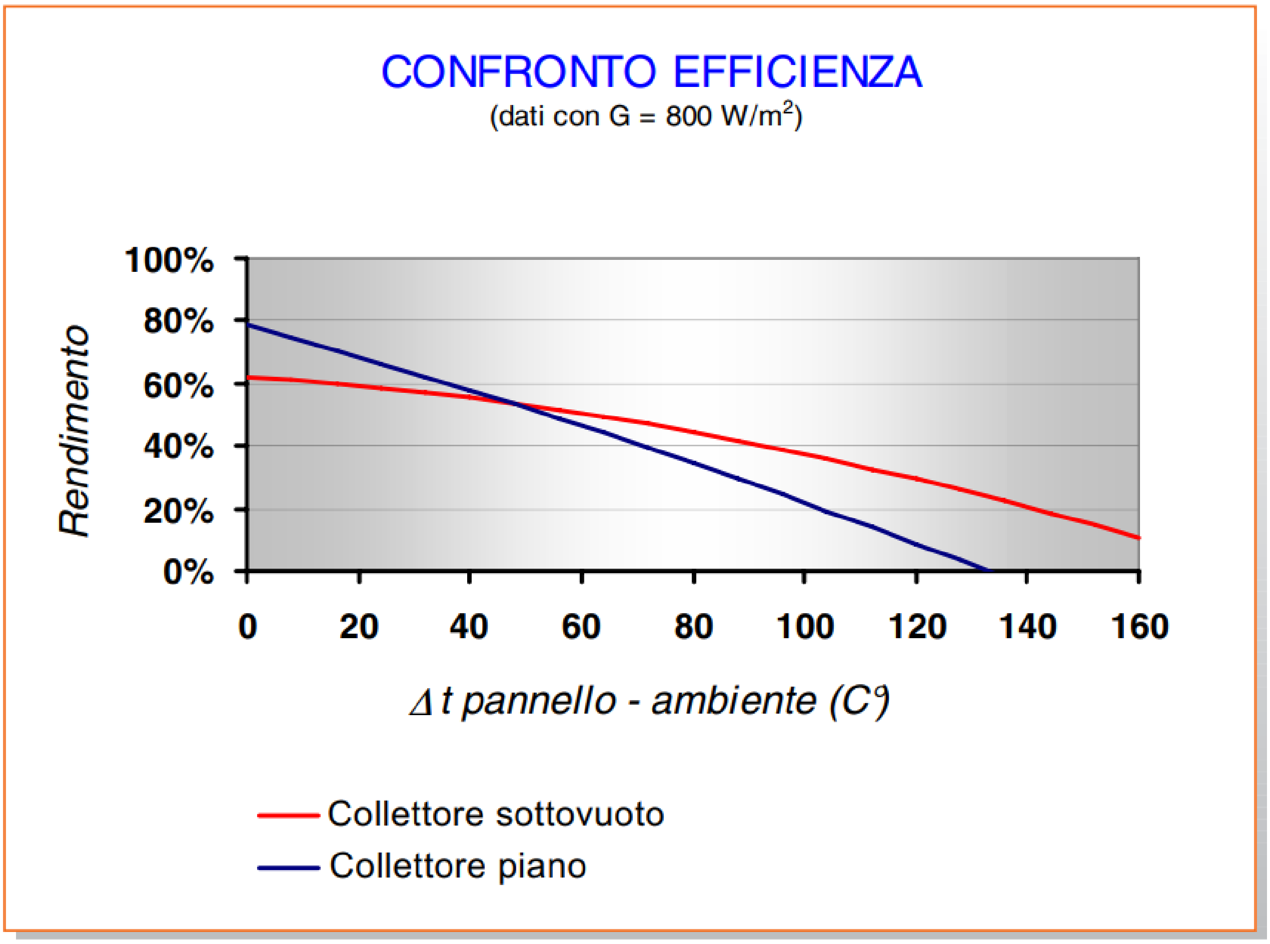


Figure 34. Solar thermal collectors efficiency graph

The efficiency of a PV panel is roughly 20% and the seasonal COP is around 4, that means that the heat is generated with 80% of efficiency on the solar irradiance input. Thus, PV combined with heat pumps are more efficient and also electricity is much more versatile, during summer the energy not used can be sold to the grid, the heat generated by thermal collector if not used is wasted.

Storage system

The storage systems available are electrical with batteries and thermal with insulated water tank.

Batteries doesn't have an impact on the consumption of the house, they are installed only for economic purposes when there is a price difference between the electricity sold to the grid and the one purchased.

On the other hand, generating heat with heat pumps is more efficient when the air is warmer, and the difference between the hottest and the coldest hours of the day can be 5-10°C in winter. So producing heat in the best moment can increase the efficiency of the process, by the way to store the heat it is necessary to produce a hotter output so in the end there is no gain available.

In the next chapter will be calculated if installing a battery can be a profitable action.

Cost optimal analysis

The cost optimal analysis allows to choose the most valuable scenario, balancing initial costs, periodical expenditures and the economical return.

The reason why the European commission decided to adopt this method for the evaluation is declared in an executive summary[30] released in 2011 and it explains:

"The concepts of cost-efficiency and cost optimality are related but different. Cost-optimality is a special case of cost-effectiveness. A measure or package of measures is cost-effective when the cost of implementation is lower than the value of the benefits that result, taken over the expected life of the measure. Both are based on comparing the costs and (priced) savings of a potential action - in this case, of introducing a particular level of minimum energy performance requirements for buildings. Future costs and savings are discounted, with the final result being a net present value. If this is positive, the action is cost-effective (for the particular set of assumptions used in the calculation). The "cost-optimal" result is that action or combination of actions that maximize the net present value. Cost optimality is relatively easy to determine for single measures operating in well-defined conditions -for example, the optimal insulation thickness for pipework operating at a constant temperature in a constant-temperature environment. It is a considerably more difficult process for complete buildings, and even more so for combinations of buildings such as a national building stock."

The first step to calculate the global cost is to define the initial cost.

Initial costs

To calculate the initial cost of the various scenarios it is necessary to evaluate the quantity of the materials, the price for the labor, and the cost of various plant.

All the prices, when possible, are extracted from the official catalogue released by the regional authorities: "Prezzario Regionale Opere Pubbliche"[31].

The expenditure is calculated only for the elements for the energetic renovation because in this case the object of the analysis is the renovation and not the cost of the whole building.

The three levels of insulation are simulated with three different materials to find the tradeoff between floor surface loss and installation cost.

The three materials are:

- Sintered polystyrene foam (**EPS**) panels with thermal conductivity 0.042 W/mK and density 10-13 kg/m^3
- Sandwich-type panels made of polyurethane rigid foam (**PIR**) self-extinguishing with bitumen-paper coating for thermal insulation of perimeter walls; thermal conductivity 0.029 W/mK.
- Panels made by rigid polyurethane foam (**polyiso**), coated on both sides with waterproof multilayer coating for thermal insulation. Thermal conductivity 0.022 W/mK

Regardless of the insulation material, some elements are constant in all cases, so these are the first to be evaluated.

Description	Area [m^2]	Adhesive [mm]	Plaster [mm]	Vapor barrier [mm]
Wall A1 brick	35,34	10	10	-
Wall A1 stone	21,69	10	10	0,3
Wall A1 concrete	6,88	10	10	0,3
Wall B1	41,14	10	10	0,3
Wall D1	36,66	10	10	0,3
Internal wall	26,6	10	10	-
Ceiling	119,13	10	-	-
Floor	137,77	10	-	-
One pitch roof	27,58	10	5	-

Table 53. List of materials installed on the wall

Item	Price	Unit	Regional price-list code
Plaster powder	2.52	€/kg	01.P02.F20
Adhesive	0.89	€/kg	01.P23.A91
Vapor barrier	2.90	€/m^2	01.P10.F55.005
Plastering work	7.25	€/m^2	01.A10.B10.005

Table 54. Construction materials price

The ceiling and the floor don't have the plaster layer because the insulation panels are not toward the inside so they can be without that coating.

Plaster powder is mixed with water in with a ratio 60% powder and 40% water, so the price decrease to 1.50 €/kg.

The cost of all these elements is calculated in the table below.

Item	Area [m^2]	Volume [m^3]	Density [kg/m^3]	Weight [kg]	Price	Cost [€]
Plaster	-	1,8211	1500	**3277,98**	1,5 €/kg	**4916,97**
Vapor Barrier	**106,38**	-	-	-	2,9 €/m^2	**308,50**
Adhesive	395,77	4,528	100	**4528**	0,89 €/kg	**402,90**
Plastering Work	**195,9**	-	-	-	7,25 €/m^2	**1420,27**
Total						**7048,64**

Table 55. Cost of various construction materials

Insulation panels cost

The thickness that each material should have to give the same grade of insulation, is calculated.

Case 1 legal minimum

Description	Area [m^2]	U ref. [W/m^{2}K]	EPS [mm]	PIR [mm]	Polyiso [mm]
Wall A1 brick	35,34	0,26	40	30	20
Wall A1 stone	21,69	0,26	60	40	30
Wall A1 concrete	6,88	0,26	140	100	80
Wall B1	41,14	0,26	50	30	30
Wall D1	36,66	0,26	120	80	60
Internal wall	26,6	0,24	140	100	70
Ceiling	119,13	0,22	160	120	80
Floor	137,77	0,26	100	60	50
One Pitch Roof	27,58	0,22	100	60	50

Table 56. Thickness of insulation panels

EPS					
Item	Thickness [mm]	Price code	Area m^2	Price [€/m^2]	Cost [€]
Panel	40	01.P09.A00.020	35,34	2,57	90,82
Panel	50	01.P09.A00.025	41,14	3,21	132,08
Panel	60	01.P09.A00.030	21,69	3,9	84,59
Panel	100	01.P09.A00.045	165,35	6,44	1064,85
Panel	120	01.P09.A00.050	36,66	7,74	283,75
Panel	140	01.P09.A00.055	33,48	9,02	302,03
Panel	160	01.P09.A02.045	119,13	17,17	2045,46
Installation	-	01.A09.G50.010	452,8	11,28	5107,58
Total					**9111.17**

Table 57. Cost of insulation panels

PIR					
Item	Thickness [mm]	Price code	Area m^2	Price [€/m^2]	Cost [€]
Panel	30	01.P09.G10.015	76,48	7,94	607,29
Panel	40	01.P09.G10.020	21,69	10,44	226,44
Panel	60	01.P09.G10.025	165,35	15,51	2564,57
Panel	80	01.P09.G35.020	36,66	28,83	1056,90
Panel	100	01.P09.G35.025	33,48	35,15	1176,99
Panel	120	01.P09.G35.030	119,13	41,23	4911,73
Installation	-	01.A09.G50.010	452,8	11,28	5107,58
Total					**15651,53**

Table 58. Cost of insulation panels

Polyiso					
Item	Thickness [mm]	Price code	Area m^2	Price [€/m^2]	Cost [€]
Panel	20	30.P50.D15.005	35,34	8,64	305,33
Panel	30	30.P50.D15.010	62,835	11,04	693,69
Panel	50	30.P50.D15.020	165,35	16,28	2691,88
Panel	60	30.P50.D15.025	36,66	19,00	696,54
Panel	70	30.P50.D15.30	26,6	21,67	576,42
Panel	80	30.P50.D15.035	126,015	24,3	3062,16
Installation	-	01.A09.G50.010	452,8	11,28	5107,58
Total					**13133,64**

Table 59. Cost of insulation panels

Case 2: 0.20 W/m²K

Description	Area [m²]	U ref. [W/m²K]	EPS [mm]	PIR [mm]	Polyiso [mm]
Wall A1 brick	35,34	0,20	100	60	50
Wall A1 stone	21,69	0,20	100	60	50
Wall A1 concrete	6,88	0,20	200	140	100
Wall B1	41,14	0,20	100	80	50
Wall D1	36,66	0,20	160	120	80
Internal wall	26,6	0,20	180	120	100
Ceiling	119,13	0,20	180	120	100
Floor	137,77	0,20	140	100	70
One Pitch Roof	27,58	0,20	120	80	60

Table 60. Thickness of insulation panels

In red the thickness that is not available in the catalogue, so it is exchanged with polyiso panels.

EPS					
Item	Thickness [mm]	Price code	Area m²	Price [€/m²]	Cost [€]
Panel	100	01.P09.A00.045	98,175	6,44	632,25
Panel	120	01.P09.A00.055	27,58	7,74	213,47
Panel	140	01.P09.A00.052	137,77	9,02	1242,69
Panel	160	01.P09.A02.045	36,66	17,17	629,45
Panel	100	30.P50.D15.045	152,615	30,25	4616,60
Installation	-	01.A09.G50.010	452,8	11,28	5107,58
Total					**12442.04**

Table 61. Cost of insulation panels

PIR					
Item	Thickness [mm]	Price code	Area m^2	Price [€/m^2]	Cost [€]
Panel	60	01.P09.G35.020	57,03	15,51	884,54
Panel	80	01.P09.G35.025	68,725	28,83	1981,34
Panel	100	01.P09.G35.030	137,77	35,15	4842,62
Panel	120	01.P09.G35.035	182,39	41,23	7519,94
Panel	100	30.P50.D15.045	6,885	30,25	208,27
Installation	-	01.A09.G50.010	452,8	11,28	5107,58
Total					**20544.28**

Table 62. Cost of insulation panels

Polyiso					
Item	Thickness [mm]	Price code	Area m^2	Price [€/m^2]	Cost [€]
Panel	50	30.P50.D15.020	98,175	16,28	1598,29
Panel	60	30.P50.D15.025	27,58	19	524,02
Panel	70	30.P50.D15.030	137,77	21,67	2985,48
Panel	80	30.P50.D15.035	36,66	24,3	890,84
Panel	100	30.P50.D15.045	152,615	30,25	4616,60
Installation	-	01.A09.G50.010	452,8	11,28	5107,58
Total					**15722.81**

Table 63. Cost of insulation panels

Case 3: 0.15 W/m²K

Description	Area [m²]	U ref. [W/m²K]	EPS [mm]	PIR [mm]	Polyiso [mm]
Wall A1 brick	35,34	0,15	160	120	80
Wall A1 stone	21,69	0,15	180	120	90
Wall A1 concrete	6,88	0,15	260	180	140
Wall B1	41,14	0,15	180	120	90
Wall D1	36,66	0,15	240	160	120
Internal wall	26,6	0,15	240	160	120
Ceiling	119,13	0,15	250	180	140
Floor	137,77	0,15	220	160	110
One Pitch Roof	27,58	0,15	200	140	100

Table 64. Thickness of insulation panels

In red the thickness that is not available in the catalogue, in this last case EPS and PIR panels cannot satisfy the requirements on almost all the structures, for this reason will be simulated only the polyiso case.

Polyiso					
Item	Thickness [mm]	Price code	Area m²	Price [€/m²]	Cost [€]
Panel	80	30.P50.D15.035	35,34	24,3	858,762
Panel	90	30.P50.D15.040	62,835	26,98	1695,288
Panel	100	30.P50.D15.045	27,58	30,25	834,295
Panel	120	30.P50.D15.050	201,03	35,56	7148,627
Panel	140	30.P50.D15.055	126,015	40,97	5162,835
Installation	-	01.A09.G50.010	452,8	11,28	5107,58
Total					**20807.39**

Table 65. Cost of insulation panels

Windows

It is calculated the cost for buying and installing the windows of the optimized configuration.

Window	Uw [W/m²K]	Glass [€/m²]	Price code	Frame [€/m²]	Price code	Price code for extra thermal perf.	**Product Cost [€/window]**
100x150	0,8	93,26	01.P20.B04.085	286	01.P20.G00.025	01.P20.G40.020	**570**
100x220	0,8	93,26	01.P20.B04.086	259	01.P20.G00.030	01.P20.G40.021	**775**
60x150	1,3	52,81	01.P20.B04.087	286	01.P20.G00.025	01.P20.G40.022	**305**
210x120	0,8	93,26	01.P20.B04.088	382	01.P20.G00.055	01.P20.G40.023	**1198**
100x150	1,3	52,81	01.P20.B04.085	282	01.P20.G00.025	01.P20.G40.020	**502**

Window	n.	Uw [W/m²K]	Installation	Price code	Glassmaker	Price code	**Final cost [€/window]**
100x150	5	0,8	28,85	01.A16.B00	51,53	01.A15.A10.015	**690**
100x220	3	0,8	28,85	01.A16.B01	51,53	01.A15.A10.016	**952**
60x150	1	1,3	28,85	01.A16.B02	51,53	01.A15.A10.017	**378**
210x120	1	0,8	28,85	01.A16.B03	51,53	01.A15.A10.018	**1400**
100x150	4	0,8	28,85	01.A16.B00	51,53	01.A15.A10.015	**623**

Table 66. Cost of windows

Total cost for windows is 10582.01 euro.

Summary results

It is now possible to calculate the whole initial cost to insulate the apartment, in the cost there are the constant cost calculated at the beginning (7048.64 euro), the cost for each insulation choice, the loss of floor area with a market price[32] of 950 €/m^2.

	EPS 0.042 W/m²K	PIR 0.029 W/m²K	Polyiso 0.022 W/m²K
Case 1	21.523,24 €	26.354,87 €	22.969,47 €
Case 2	26.855,98 €	32.868,27 €	27.101,70 €
Case 3			34.448,65 €

Table 67. Initial investment for wall insulation

The PIR panels are the most expensive choice therefore this option is discharged. The cost difference between EPS and polyiso is small (1446 euro in case 1 and246 euro in case 2), if the house market had a small raise and the material price decreased, two such likely events, the most convenient would become the polyiso. Then for the continuation of this thesis the polyiso cases will be the reference.

Adding the cost for the windows the results are shown in the table below.

	EPS 0.042 W/m²K	PIR 0.029 W/m²K	Polyiso 0.022 W/m²K
Case 1	32.105,25 €	36.936,88 €	33.551,48 €
Case 2	37.437,99 €	43.450,28 €	37.683,71 €
Case 3	-	-	45.030,66 €

Table 68. Initial investment of insulation and windows

Cost of the plants

With reference to the plants simulated in the previous chapter their cost is now assessed. It is noteworthy that the different insulation cases have a different heat pump model, by the way they are in the same power class inside the regional price catalogue.

Heat pump			
Item	Price code	Price	Cost
Heat pump	03.P13.L03.005	7.220,40 €	7.220,40 €
DHW Heat pump	Average market price	1500 ,00€	1500,00 €
Installation	03.A12.F01.005	811,52 €	811,52 €
Total			**9.531,92 €**

Table 69. Investment for heat pumps

Radiant Floor			
Item	Price code	Price	Cost
Radiant floor material	03.P13.C01.020	36,55 €/m^2	4970,80 €
Subfloor preparation	03.A05.A03.005	64,45 €/m^2	8765,20 €
Tubes installation	03.A12.C01.005	25% of material	1242,70 €
Total			**14978,70 €**

Table 70. Investment for radiant floor

Heat recuperator			
Item	Price code	Price	Cost
Heat recuperator 150 m^3/h	03.P16.A01.005	2.291,83 €	2.291,83 €
Silencer	03.P16.A05.010	227,88 €	227,88 €
Aspiration tower	03.P16.A05.015	1.430,69 €	1.430,69 €
Ventilation duct	03.P16.A04.010	5,65€/m	339,00 €
Installation	03.A15.A01.005	202,88 €	202,88 €
Total			**4.492,28 €**

Table 71. Investment for heat recuperator

The PV generation has been seen in two options: a plant that generates the same amount of energy consumed or the maximum size installable on the roof.

The maximum size is instead 15kWp.

15 kWp PV plant			
Item	Price code	Price	Cost
PV panel	03.P14.A06.005	1,8 €/Wp	27000,00
PV installation	03.A13.A01.010	92,14 €/m^2	8016,18 €
Power optimizer	03.P14.A23.010	75 €/two panels	2625,00 €
15 kW Inverter	03.P14.A14.035	1963,68 €	1963,68 €
Inverter installation	03.A13.A03.005	270,51 €	270,51 €
Total			**39875,37 €**

Table 72. Investment for max size PV plant

Following the method shown for the 15 kWp plant, the cost for the various tailored PV installation are calculated and reported in the table below.

	Case 1: legal minimum	Case 2: 0.20 W/m^2K	Case 3: 0.15W/m^2K
No heath recuperator	26 PV panels - 5.6 kWp	24 PV panels - 5.2kWp	22 PV panels - 4.7 kWp
	15893.83 €	**14816,33 €**	**13541,81 €**
With heath recuper.	24 PV panels - 5.2kWp	23 PV panels - 5kWp	21 PV panels - 4.5 kWp
	14816,33 €	**14080,56 €**	**13003,06 €**

Table 73. Investment for PV panels

The references for the inverter are: 5kW inverter at 1418,72 € with price code 03.P14.A14.010 and 6kW inverter at 1615,73 € with price code 03.P14.A14.015.

For the minimum renewable generation, the cost is the 60% of the prices in the table above.

Battery			
Item	Price code	Price	Cost
7kWh battery all inclusive	Market research[33]	6690.00 €/	6690.00 €/
3 kWh battery all inclusive	Market research	2000.00 €/	2000.00 €/

Table 74. Investment for batteries

Economic evaluation

The economic evaluation is done with reference to the standard EN 15459:2007 and to the European Commission's guidelines[34]. The global costs are calculated for all the possible combinations of the various technologies seen along this thesis.

Name	Insulation	Heat recuperator	PV	Battery	Caption
A1	Legal minimum	NO	Covers 60% of consumption	NO	
A2	Legal minimum	NO	Covers 100% of consumption	NO	
A3	Legal minimum	NO	Covers 100% of consumption	YES	
A4	Legal minimum	NO	Max size	NO	
A5	Legal minimum	NO	Max size	YES	
B1	Legal minimum	YES	Covers 60% of consumption	NO	
B2	Legal minimum	YES	Covers 100% of consumption	NO	
B3	Legal minimum	YES	Covers 100% of consumption	YES	
B4	Legal minimum	YES	Max size	NO	
B5	Legal minimum	YES	Max size	YES	

Table 75. Description of simulated scenarios

Name	Insulation	Heat recuperator	PV	Battery	Caption
C1	0.20 W/m^{2}K	NO	Covers 60% of consumption	NO	
C2	0.20 W/m^{2}K	NO	Covers 100% of consumption	NO	
C3	0.20 W/m^{2}K	NO	Covers 100% of consumption	YES	
C4	0.20 W/m^{2}K	NO	Max size	NO	
C5	0.20 W/m^{2}K	NO	Max size	YES	
D1	0.20 W/m^{2}K	YES	Covers 60% of consumption	NO	
D2	0.20 W/m^{2}K	YES	Covers 100% of consumption	NO	
D3	0.20 W/m^{2}K	YES	Covers 100% of consumption	YES	
D4	0.20 W/m^{2}K	YES	Max size	NO	
D5	0.20 W/m^{2}K	YES	Max size	YES	

Table 76. Description of simulated scenarios

Name	Insulation	Heat recuperator	PV	Battery	Caption
E1	0.15 W/m^{2}K	NO	Covers 60% of consumption	NO	
E2	0.15 W/m^{2}K	NO	Covers 100% of consumption	NO	
E3	0.15 W/m^{2}K	NO	Covers 100% of consumption	YES	
E4	0.15 W/m^{2}K	NO	Max size	NO	
E5	0.15 W/m^{2}K	NO	Max size	YES	
F1	0.15 W/m^{2}K	YES	Covers 60% of consumption	NO	
F2	0.15 W/m^{2}K	YES	Covers 100% of consumption	NO	
F3	0.15 W/m^{2}K	YES	Covers 100% of consumption	YES	
F4	0.15 W/m^{2}K	YES	Max size	NO	
F5	0.15 W/m^{2}K	YES	Max size	YES	

Table 77. Description of simulated scenarios

Financial Data

The financial data that define the context of the analysis are:

- Duration of the calculation, 30 years
- Inflation rate[35], 5 %
- Market interest rate[36], 6 %
- Rate of development of human operation costs, 5 %
- Rate of development of energy prices, 5 % (gas and electricity)
- Electricity market price[37] 100 €/MWh (0.10 €/kWh)
- Electricity price for users[38] 0.166 €/kWh.
- European reference discount rate for building operations[39] 4%

Global cost

For this calculation, all the data follow the instruction of the standard EN 15459:2007 and the European guidelines[34].

All the elements installed in the house, their life span and maintenance cost are listed below; unless otherwise specified all the data are extracted from the standard EN 15459:2007.

Description	Life Span [year]	Annual maintenance
Windows	30	-
Insulation	50	-
Heat pump	15	2%
Radiant floor	50	2%
Ventilation and heat recuperator	15	4%
Small medium PV plant	30 [42]	1.45% [41]
Large PV plant	30 [42]	1% [41]
Battery	15	-

Table 78. Maintance cost

For the discount rate, the reference value is used at 4%

A cases

Case A1			
Investment cost			
Description	**Cost**		**Final value**
Windows	10.582,01 €		10.582,01 €
Insulation	22.969,47 €		22.969,47 €
Heat pump	9.531,92 €		9.531,92 €
Radiant floor	14.978,70 €		14.978,70 €
Minimum PV plant	9.500,12 €		9.500,12 €
Total			**67.597,93 €**
Replacement cost			
Description	**Cost**	**Discount rate coef.**	**Final value**
Replacement at 15 years	9.531,92 €	0,555	5.292,74 €
Residual value	-15.179,27 €	0,308	-4.680,05 €
Annual cost			
Description	**Cost**	**Present value factor**	**Final value**
Maintenance	628,49 €	17,29	10.866,57 €
Energy cost			
Description	**Cost**	**Present value factor**	**Final value**
Electricity	388,94 €	17,29	6.725 €
Global cost			
85.802 €			

Table 79. A1 scenario global cost

Case A2			
Investment cost			
Description	**Cost**		**Final value**
Windows	10.582,01 €		10.582,01 €
Insulation	22.969,47 €		22.969,47 €
Heat pump	9.531,92 €		9.531,92 €
Radiant floor	14.978,70 €		14.978,70 €
Tailored PV plant	15.893,83 €		15.893,83 €
Total			**73.955,93 €**
Replacement cost			
Description	**Cost**	**Discount rate coef.**	**Final value**
Replacement at 15 years	9.531,92 €	0,555	5.292,74 €
Residual value	-15.179,27 €	0,308	-4.680,05 €
Annual cost			
Description	**Cost**	**Present value factor**	**Final value**
Maintenance	720,67 €	17,29	12.461,90 €
Energy cost			
Description	**Cost**	**Present value factor**	**Final value**
Electricity	210,00 €	17,29	3.631,33 €
Global cost			
90.661,84 €			

Table 80. A2 scenario global cost

Case A3			
Investment cost			
Description	**Cost**		**Final value**
Windows	10.582,01 €		10.582,01 €
Insulation	22.969,47 €		22.969,47 €
Heat pump	9.531,92 €		9.531,92 €
Radiant floor	14.978,70 €		14.978,70 €
Tailored PV plant	15.893,83 €		15.893,83 €
Battery 3kWh	2.000,00 €		2.000,00 €
Total			**75.955,93 €**
Replacement cost			
Description	**Cost**	**Discount rate coef.**	**Final value**
Replacement at 15 years	11.531,92 €	0,5552645	6.403,27 €
Residual value	-15.179,27 €	0,308	-4.680,05 €
Annual cost			
Description	**Cost**	**Present value factor**	**Final value**
Maintenance	720,67 €	17,29	12.461,90 €
Energy cost			
Description	**Cost**	**Present value factor**	**Final value**
Electricity	161,00 €	17,29	2.784,02 €
Global cost			
92.925,06 €			

Table 81. A3 scenario global cost

Case A4			
Investment cost			
Description	**Cost**		**Final value**
Windows	10.582,01 €		10.582,01 €
Insulation	22.969,47 €		22.969,47 €
Heat pump	9.531,92 €		9.531,92 €
Radiant floor	14.978,70 €		14.978,70 €
Max size PV plant	39.875,37 €		39.875,37 €
Total			**97.937,47 €**
Replacement cost			
Description	**Cost**	**Discount rate coef.**	**Final value**
Replacement at 15 years	9.531,92 €	0,555	5.292,74 €
Residual value	-15.179,27 €	0,308	-4.680,05 €
Annual cost			
Description	**Cost**	**Present value factor**	**Final value**
Maintenance	888,97 €	17,29	15.372,03 €
Energy cost			
Description	**Cost**	**Present value factor**	**Final value**
Electricity	-771,00 €	17,29	-13.332,16 €
Global cost			
100.590,03 €			

Table 82. A4 scenario global cost

Case A5			
Investment cost			
Description	**Cost**		**Final value**
Windows	10.582,01 €		10.582,01 €
Insulation	22.969,47 €		22.969,47 €
Heat pump	9.531,92 €		9.531,92 €
Radiant floor	14.978,70 €		14.978,70 €
Max size PV plant	39.875,37 €		39.875,37 €
Battery 7kWh	6.690,00 €		6.690,00 €
Total			**104.627,47 €**
Replacement cost			
Description	**Cost**	**Discount rate coef.**	**Final value**
Replacement at 15 years	16.221,92 €	0,5552645	9.007,46 €
Residual value	-15.179,27 €	0,308	-4.680,05 €
Annual cost			
Description	**Cost**	**Present value factor**	**Final value**
Maintenance	888,97 €	17,29	15.372,03 €
Energy cost			
Description	**Cost**	**Present value factor**	**Final value**
Electricity	-885,00 €	17,29	-15.303,45 €
Global cost			
109.023,46 €			

Table 83. A5 scenario global cost

B cases

Case B1			
Investment cost			
Description	**Cost**		**Final value**
Windows	10.582,01 €		10.582,01 €
Insulation	22.969,47 €		22.969,47 €
Heat pump	9.531,92 €		9.531,92 €
Radiant floor	14.978,70 €		14.978,70 €
Heat recuperator	4.492,28 €		4.492,28 €
Minimum PV plant	9.537,15 €		9.537,15 €
Total			**71.443,51 €**
Replacement cost			
Description	**Cost**	**Discount rate coef.**	**Final value**
Replacement at 15 years	14.024,20 €	0,5552645	7.787,14 €
Residual value	-15.179,27 €	0,308	-4.680,05 €
Annual cost			
Description	**Cost**	**Present value factor**	**Final value**
Maintenance	798,80 €	17,29	13.811,30 €
Energy cost			
Description	**Cost**	**Present value factor**	**Final value**
Electricity	350,40 €	17,29	6.058 €
Global cost			
94.420 €			

Table 84. B1 scenario global cost

Case B2			
Investment cost			
Description	**Cost**		**Final value**
Windows	10.582,01 €		10.582,01 €
Insulation	22.969,47 €		22.969,47 €
Heat pump	9.531,92 €		9.531,92 €
Radiant floor	14.978,70 €		14.978,70 €
Heat recuperator	4.492,28 €		4.492,28 €
Tailored PV plant	15.893,83 €		15.893,83 €
Total			**78.448,21 €**
Replacement cost			
Description	**Cost**	**Discount rate coef.**	**Final value**
Replacement at 15 years	14.024,20 €	0,5552645	7.787,14 €
Residual value	-15.179,27 €	0,308	-4.680,05 €
Annual cost			
Description	**Cost**	**Present value factor**	**Final value**
Maintenance	900,36 €	17,29	15.569,13 €
Energy cost			
Description	**Cost**	**Present value factor**	**Final value**
Electricity	195,00 €	17,29	3.371,95 €
Global cost			
100.496,37 €			

Table 85. B2 scenario global cost

Case B3			
Investment cost			
Description	**Cost**		**Final value**
Windows	10.582,01 €		10.582,01 €
Insulation	22.969,47 €		22.969,47 €
Heat pump	9.531,92 €		9.531,92 €
Radiant floor	14.978,70 €		14.978,70 €
Heat recuperator	4.492,28 €		4.492,28 €
Tailored PV plant	15.893,83 €		15.893,83 €
Battery 3kWh	2.000,00 €		2.000,00 €
Total			**80.448,21 €**
Replacement cost			
Description	**Cost**	**Discount rate coef.**	**Final value**
Replacement at 15 years	16.024,20 €	0,5552645	8.897,67 €
Residual value	-15.179,27 €	0,308	-4.680,05 €
Annual cost			
Description	**Cost**	**Present value factor**	**Final value**
Maintenance	900,36 €	17,29	15.569,13 €
Energy cost			
Description	**Cost**	**Present value factor**	**Final value**
Electricity	146,00 €	17,29	2.524,64 €
Global cost			
102.759,59 €			

Table 86. B3 scenario global cost

Case B4			
Investment cost			
Description	**Cost**		**Final value**
Windows	10.582,01 €		10.582,01 €
Insulation	22.969,47 €		22.969,47 €
Heat pump	9.531,92 €		9.531,92 €
Radiant floor	14.978,70 €		14.978,70 €
Radiant floor	14.978,70 €		14.978,70 €
Max size PV plant	39.875,37 €		39.875,37 €
Total			**102.429,75 €**
Replacement cost			
Description	**Cost**	**Discount rate coef.**	**Final value**
Replacement at 15 years	14.024,20 €	0,5552645	7.787,14 €
Residual value	-15.179,27 €	0,308	-4.680,05 €
Annual cost			
Description	**Cost**	**Present value factor**	**Final value**
Maintenance	1.068,66 €	17,29	18.479,26 €
Energy cost			
Description	**Cost**	**Present value factor**	**Final value**
Electricity	-828,00 €	17,29	-14.317,80 €
Global cost			
109.698,29 €			

Table 87. B4 scenario global cost

Case B5			
Investment cost			
Description	**Cost**		**Final value**
Windows	10.582,01 €		10.582,01 €
Insulation	22.969,47 €		22.969,47 €
Heat pump	9.531,92 €		9.531,92 €
Radiant floor	14.978,70 €		14.978,70 €
Max size PV plant	39.875,37 €		39.875,37 €
Battery 7kWh	6.690,00 €		6.690,00 €
Total			**109.119,75 €**
Replacement cost			
Description	**Cost**	**Discount rate coef.**	**Final value**
Replacement at 15 years	20.714,20 €	0,5552645	11.501,86 €
Residual value	-15.179,27 €	0,308	-4.680,05 €
Annual cost			
Description	**Cost**	**Present value factor**	**Final value**
Maintenance	1.068,66 €	17,29	18.479,26 €
Energy cost			
Description	**Cost**	**Present value factor**	**Final value**
Electricity	-941,00 €	17,29	-16.271,80 €
Global cost			
118.149,01 €			

Table 88. B5 scenario global cos

C cases

Case C1			
Investment cost			
Description	**Cost**		**Final value**
Windows	10.582,01 €		10.582,01 €
Insulation	27.101,70 €		27.101,70 €
Heat pump	9.531,92 €		9.531,92 €
Radiant floor	14.978,70 €		14.978,70 €
Minimum PV plant	8.889,6 €		8.889,6 €
Total			**71.083,23 €**
Replacement cost			
Description	**Cost**	**Discount rate coef.**	**Final value**
Replacement at 15 years	9.531,92 €	0,5552645	5.292,74 €
Residual value	-16.832,16 €	0,30831867	-5.189,67 €
Annual cost			
Description	**Cost**	**Present value factor**	**Final value**
Maintenance	619,11 €	17,29	10.704,44 €
Energy cost			
Description	**Cost**	**Present value factor**	**Final value**
Electricity	351,06 €	17,29	6.070 €
Global cost			
87.960 €			

Table 89. C1 scenario global cost

Case C2			
Investment cost			
Description	**Cost**		**Final value**
Windows	10.582,01 €		10.582,01 €
Insulation	27.101,70 €		27.101,70 €
Heat pump	9.531,92 €		9.531,92 €
Radiant floor	14.978,70 €		14.978,70 €
Tailored PV plant	14.816,33 €		14.816,33 €
Total			**77.010,66 €**
Replacement cost			
Description	**Cost**	**Discount rate coef.**	**Final value**
Replacement at 15 years	9.531,92 €	0,5552645	5.292,74 €
Residual value	-16.832,16 €	0,30831867	-5.189,67 €
Annual cost			
Description	**Cost**	**Present value factor**	**Final value**
Maintenance	705,05 €	17,29	12.191,73 €
Energy cost			
Description	**Cost**	**Present value factor**	**Final value**
Electricity	198,00 €	17,29	3.423,82 €
Global cost			
92.729,28 €			

Table 90. C2 scenario global cost

Case C3			
Investment cost			
Description	**Cost**		**Final value**
Windows	10.582,01 €		10.582,01 €
Insulation	27.101,70 €		27.101,70 €
Heat pump	9.531,92 €		9.531,92 €
Radiant floor	14.978,70 €		14.978,70 €
Tailored PV plant	14.816,33 €		14.816,33 €
Battery 3kWh	2.000,00 €		2.000,00 €
Total			**79.010,66 €**
Replacement cost			
Description	**Cost**	**Discount rate coef.**	**Final value**
Replacement at 15 years	11.531,92 €	0,5552645	6.403,27 €
Residual value	-16.832,16 €	0,30831867	-5.189,67 €
Annual cost			
Description	**Cost**	**Present value factor**	**Final value**
Maintenance	705,05 €	17,29	12.191,73 €
Energy cost			
Description	**Cost**	**Present value factor**	**Final value**
Electricity	149,00 €	17,29	2.576,51 €
Global cost			
94.992,50 €			

Table 91. C3 scenario global cost

Case C4			
Investment cost			
Description	**Cost**		**Final value**
Windows	10.582,01 €		10.582,01 €
Insulation	27.101,70 €		27.101,70 €
Heat pump	9.531,92 €		9.531,92 €
Radiant floor	14.978,70 €		14.978,70 €
Max size PV plant	39.875,37 €		39.875,37 €
Total			**102.069,70 €**
Replacement cost			
Description	**Cost**	**Discount rate coef.**	**Final value**
Replacement at 15 years	9.531,92 €	0,5552645	5.292,74 €
Residual value	-16.832,16 €	0,30831867	-5.189,67 €
Annual cost			
Description	**Cost**	**Present value factor**	**Final value**
Maintenance	888,97 €	17,29	15.372,03 €
Energy cost			
Description	**Cost**	**Present value factor**	**Final value**
Electricity	-825,00 €	17,29	-14.265,93 €
Global cost			
103.278,87 €			

Table 92. C4 scenario global cost

Case C5			
Investment cost			
Description	**Cost**		**Final value**
Windows	10.582,01 €		10.582,01 €
Insulation	27.101,70 €		27.101,70 €
Heat pump	9.531,92 €		9.531,92 €
Radiant floor	14.978,70 €		14.978,70 €
Max size PV plant	39.875,37 €		39.875,37 €
Battery 7kWh	6.690,00 €		6.690,00 €
Total			**108.759,70 €**
Replacement cost			
Description	**Cost**	**Discount rate coef.**	**Final value**
Replacement at 15 years	16.221,92 €	0,5552645	9.007,46 €
Residual value	-16.832,16 €	0,30831867	-5.189,67 €
Annual cost			
Description	**Cost**	**Present value factor**	**Final value**
Maintenance	888,97 €	17,29	15.372,03 €
Energy cost			
Description	**Cost**	**Present value factor**	**Final value**
Electricity	-938,00 €	17,29	-16.219,93 €
Global cost			
111.729,59 €			

Table 93. C5 scenario global cost

D cases

Case D1			
Investment cost			
Description	**Cost**		**Final value**
Windows	10.582,01 €		10.582,01 €
Insulation	27.101,70 €		27.101,70 €
Heat pump	9.531,92 €		9.531,92 €
Radiant floor	14.978,70 €		14.978,70 €
Heat recuperator	4.492,28 €		4.492,28 €
Minimum PV plant	8.448,31 €		8.448,31 €
Total			**75.575,51 €**
Replacement cost			
Description	**Cost**	**Discount rate coef.**	**Final value**
Replacement at 15 years	14.024,20 €	0,5552645	7.787,14 €
Residual value	-16.832,16 €	0,30831867	-5.189,67 €
Annual cost			
Description	**Cost**	**Present value factor**	**Final value**
Maintenance	798,80 €	17,29	13.811,30 €
Energy cost			
Description	**Cost**	**Present value factor**	**Final value**
Electricity	331,20 €	17,29	5.727 €
Global cost			
97.711 €			

Table 94. D1 scenario global cost

Case D2			
Investment cost			
Description	**Cost**		**Final value**
Windows	10.582,01 €		10.582,01 €
Insulation	27.101,70 €		27.101,70 €
Heat pump	9.531,92 €		9.531,92 €
Radiant floor	14.978,70 €		14.978,70 €
Heat recuperator	4.492,28 €		4.492,28 €
Tailored PV plant	14.080,56 €		14.080,56 €
Total			**80.767,17 €**
Replacement cost			
Description	**Cost**	**Discount rate coef.**	**Final value**
Replacement at 15 years	14.024,20 €	0,5552645	7.787,14 €
Residual value	-16.832,16 €	0,30831867	-5.189,67 €
Annual cost			
Description	**Cost**	**Present value factor**	**Final value**
Maintenance	874,07 €	17,29	15.114,48 €
Energy cost			
Description	**Cost**	**Present value factor**	**Final value**
Electricity	175,00 €	17,29	3.026,11 €
Global cost			
101.505,22 €			

Table 95. D2 scenario global cost

Case D3			
Investment cost			
Description	**Cost**		**Final value**
Windows	10.582,01 €		10.582,01 €
Insulation	27.101,70 €		27.101,70 €
Heat pump	9.531,92 €		9.531,92 €
Radiant floor	14.978,70 €		14.978,70 €
Heat recuperator	4.492,28 €		4.492,28 €
Tailored PV plant	14.080,56 €		14.080,56 €
Battery 3kWh	2.000,00 €		2.000,00 €
Total			**82.767,17 €**
Replacement cost			
Description	**Cost**	**Discount rate coef.**	**Final value**
Replacement at 15 years	16.024,20 €	0,5552645	8.897,67 €
Residual value	-16.832,16 €	0,30831867	-5.189,67 €
Annual cost			
Description	**Cost**	**Present value factor**	**Final value**
Maintenance	874,07 €	17,29	15.114,48 €
Energy cost			
Description	**Cost**	**Present value factor**	**Final value**
Electricity	125,00 €	17,29	2.161,50 €
Global cost			
103.751,15 €			

Table 96. D3 scenario global cost

Case D4			
Investment cost			
Description	**Cost**		**Final value**
Windows	10.582,01 €		10.582,01 €
Insulation	27.101,70 €		27.101,70 €
Heat pump	9.531,92 €		9.531,92 €
Radiant floor	14.978,70 €		14.978,70 €
Radiant floor	14.978,70 €		14.978,70 €
Max size PV plant	39.875,37 €		39.875,37 €
Total			**106.561,98 €**
Replacement cost			
Description	**Cost**	**Discount rate coef.**	**Final value**
Replacement at 15 years	14.024,20 €	0,5552645	7.787,14 €
Residual value	-16.832,16 €	0,30831867	-5.189,67 €
Annual cost			
Description	**Cost**	**Present value factor**	**Final value**
Maintenance	1.068,66 €	17,29	18.479,26 €
Energy cost			
Description	**Cost**	**Present value factor**	**Final value**
Electricity	-869,00 €	17,29	-15.026,78 €
Global cost			
112.611,93 €			

Table 97. D4 scenario global cost

Case D5			
Investment cost			
Description	**Cost**		**Final value**
Windows	10.582,01 €		10.582,01 €
Insulation	27.101,70 €		27.101,70 €
Heat pump	9.531,92 €		9.531,92 €
Radiant floor	14.978,70 €		14.978,70 €
Max size PV plant	39.875,37 €		39.875,37 €
Battery 7kWh	6.690,00 €		6.690,00 €
Total			**113.251,98 €**
Replacement cost			
Description	**Cost**	**Discount rate coef.**	**Final value**
Replacement at 15 years	20.714,20 €	0,5552645	11.501,86 €
Residual value	-16.832,16 €	0,30831867	-5.189,67 €
Annual cost			
Description	**Cost**	**Present value factor**	**Final value**
Maintenance	1.068,66 €	17,29	18.479,26 €
Energy cost			
Description	**Cost**	**Present value factor**	**Final value**
Electricity	-980,00 €	17,29	-16.946,19 €
Global cost			
121.097,24 €			

Table 98. D5 scenario global cost

E cases

Case E1			
Investment cost			
Description	**Cost**		**Final value**
Windows	10.582,01 €		10.582,01 €
Insulation	34.448,65 €		34.448,65 €
Heat pump	9.531,92 €		9.531,92 €
Radiant floor	14.978,70 €		14.978,70 €
Minimum PV plant	8.124,60 €		8.124,60 €
Total			**77.640,63 €**
Replacement cost			
Description	**Cost**	**Discount rate coef.**	**Final value**
Replacement at 15 years	9.531,92 €	0,5552645	5.292,74 €
Residual value	-19.770,94 €	0,30831867	-6.095,75 €
Annual cost			
Description	**Cost**	**Present value factor**	**Final value**
Maintenance	607,66 €	17,29	10.506,48 €
Energy cost			
Description	**Cost**	**Present value factor**	**Final value**
Electricity	320,91 €	17,29	5.549 €
Global cost			
92.893 €			

Table 99. E1 scenario global cost

Case E2			
Investment cost			
Description	**Cost**		**Final value**
Windows	10.582,01 €		10.582,01 €
Insulation	34.448,65 €		34.448,65 €
Heat pump	9.531,92 €		9.531,92 €
Radiant floor	14.978,70 €		14.978,70 €
Tailored PV plant	13541,81 €		13541,81 €
Total			**83.083,09 €**
Replacement cost			
Description	**Cost**	**Discount rate coef.**	**Final value**
Replacement at 15 years	9.531,92 €	0,5552645	5.292,74 €
Residual value	-19.770,94 €	0,30831867	-6.095,75 €
Annual cost			
Description	**Cost**	**Present value factor**	**Final value**
Maintenance	686,57 €	17,29	11.872,17 €
Energy cost			
Description	**Cost**	**Present value factor**	**Final value**
Electricity	231,00 €	17,29	3.994,46 €
Global cost			
98.146,70 €			

Table 100. E2 scenario global cost

Case E3			
Investment cost			
Description	**Cost**		**Final value**
Windows	10.582,01 €		10.582,01 €
Insulation	34.448,65 €		34.448,65 €
Heat pump	9.531,92 €		9.531,92 €
Radiant floor	14.978,70 €		14.978,70 €
Tailored PV plant	13541,81 €		13541,81 €
Battery 3kWh	2.000,00 €		2.000,00 €
Total			**85.083,09 €**
Replacement cost			
Description	**Cost**	**Discount rate coef.**	**Final value**
Replacement at 15 years	11.531,92 €	0,5552645	6.403,27 €
Residual value	-19.770,94 €	0,30831867	-6.095,75 €
Annual cost			
Description	**Cost**	**Present value factor**	**Final value**
Maintenance	686,57 €	17,29	11.872,17 €
Energy cost			
Description	**Cost**	**Present value factor**	**Final value**
Electricity	185,00 €	17,29	3.199,03 €
Global cost			
100.461,80 €			

Table 101. E3 scenario global cost

Case E4			
Investment cost			
Description	**Cost**		**Final value**
Windows	10.582,01 €		10.582,01 €
Insulation	34.448,65 €		34.448,65 €
Heat pump	9.531,92 €		9.531,92 €
Radiant floor	14.978,70 €		14.978,70 €
Max size PV plant	39.875,37 €		39.875,37 €
Total			**109.416,65 €**
Replacement cost			
Description	**Cost**	**Discount rate coef.**	**Final value**
Replacement at 15 years	9.531,92 €	0,5552645	5.292,74 €
Residual value	-19.770,94 €	0,30831867	-6.095,75 €
Annual cost			
Description	**Cost**	**Present value factor**	**Final value**
Maintenance	888,97 €	17,29	15.372,03 €
Energy cost			
Description	**Cost**	**Present value factor**	**Final value**
Electricity	-836,00 €	17,29	-14.456,14 €
Global cost			
109.529,53 €			

Table 102. E4 scenario global cost

Case E5			
Investment cost			
Description	**Cost**		**Final value**
Windows	10.582,01 €		10.582,01 €
Insulation	34.448,65 €		34.448,65 €
Heat pump	9.531,92 €		9.531,92 €
Radiant floor	14.978,70 €		14.978,70 €
Max size PV plant	39.875,37 €		39.875,37 €
Battery 7kWh	6.690,00 €		6.690,00 €
Total			**116.106,65 €**
Replacement cost			
Description	**Cost**	**Discount rate coef.**	**Final value**
Replacement at 15 years	16.221,92 €	0,5552645	9.007,46 €
Residual value	-19.770,94 €	0,30831867	-6.095,75 €
Annual cost			
Description	**Cost**	**Present value factor**	**Final value**
Maintenance	888,97 €	17,29	15.372,03 €
Energy cost			
Description	**Cost**	**Present value factor**	**Final value**
Electricity	-950,00 €	17,29	-16.427,43 €
Global cost			
117.962,96 €			

Table 103. E5 scenario global cost

F cases

Case F1			
Investment cost			
Description	**Cost**		**Final value**
Windows	10.582,01 €		10.582,01 €
Insulation	34.448,65 €		34.448,65 €
Heat pump	9.531,92 €		9.531,92 €
Radiant floor	14.978,70 €		14.978,70 €
Heat recuperator	4.492,28 €		4.492,28 €
Minimum PV plant	8.124,60 €		8.124,60 €
Total			**82.132,91 €**
Replacement cost			
Description	**Cost**	**Discount rate coef.**	**Final value**
Replacement at 15 years	14.024,20 €	0,5552645	7.787,14 €
Residual value	-19.770,94 €	0,30831867	-6.095,75 €
Annual cost			
Description	**Cost**	**Present value factor**	**Final value**
Maintenance	787,35 €	17,29	13.613,34 €
Energy cost			
Description	**Cost**	**Present value factor**	**Final value**
Electricity	303,18 €	17,29	5.242 €
Global cost			
102.680 €			

Table 104. F1 scenario global cost

Case F2			
Investment cost			
Description	**Cost**		**Final value**
Windows	10.582,01 €		10.582,01 €
Insulation	34.448,65 €		34.448,65 €
Heat pump	9.531,92 €		9.531,92 €
Radiant floor	14.978,70 €		14.978,70 €
Heat recuperator	4.492,28 €		4.492,28 €
Tailored PV plant	13.003,06 €		13.003,06 €
Total			**87.036,62 €**
Replacement cost			
Description	**Cost**	**Discount rate coef.**	**Final value**
Replacement at 15 years	14.024,20 €	0,5552645	7.787,14 €
Residual value	-19.770,94 €	0,30831867	-6.095,75 €
Annual cost			
Description	**Cost**	**Present value factor**	**Final value**
Maintenance	858,45 €	17,29	14.844,31 €
Energy cost			
Description	**Cost**	**Present value factor**	**Final value**
Electricity	213,00 €	17,29	3.683,20 €
Global cost			
107.255,52 €			

Table 105. F2 scenario global cost

Case F3			
Investment cost			
Description	**Cost**		**Final value**
Windows	10.582,01 €		10.582,01 €
Insulation	34.448,65 €		34.448,65 €
Heat pump	9.531,92 €		9.531,92 €
Radiant floor	14.978,70 €		14.978,70 €
Heat recuperator	4.492,28 €		4.492,28 €
Tailored PV plant	13.003,06 €		13.003,06 €
Battery 3kWh	2.000,00 €		2.000,00 €
Total			**89.036,62 €**
Replacement cost			
Description	**Cost**	**Discount rate coef.**	**Final value**
Replacement at 15 years	16.024,20 €	0,5552645	8.897,67 €
Residual value	-19.770,94 €	0,30831867	-6.095,75 €
Annual cost			
Description	**Cost**	**Present value factor**	**Final value**
Maintenance	858,45 €	17,29	14.844,31 €
Energy cost			
Description	**Cost**	**Present value factor**	**Final value**
Electricity	166,00 €	17,29	2.870,48 €
Global cost			
109.553,33 €			

Table 106. F3 scenario global cost

Case F4			
Investment cost			
Description	**Cost**		**Final value**
Windows	10.582,01 €		10.582,01 €
Insulation	34.448,65 €		34.448,65 €
Heat pump	9.531,92 €		9.531,92 €
Radiant floor	14.978,70 €		14.978,70 €
Radiant floor	14.978,70 €		14.978,70 €
Max size PV plant	39.875,37 €		39.875,37 €
Total			**113.908,93 €**
Replacement cost			
Description	**Cost**	**Discount rate coef.**	**Final value**
Replacement at 15 years	14.024,20 €	0,5552645	7.787,14 €
Residual value	-19.770,94 €	0,30831867	-6.095,75 €
Annual cost			
Description	**Cost**	**Present value factor**	**Final value**
Maintenance	1.068,66 €	17,29	18.479,26 €
Energy cost			
Description	**Cost**	**Present value factor**	**Final value**
Electricity	-875,00 €	17,29	-15.130,53 €
Global cost			
118.949,05 €			

Table 107. F4 scenario global cost

Case F5			
Investment cost			
Description	**Cost**		**Final value**
Windows	10.582,01 €		10.582,01 €
Insulation	34.448,65 €		34.448,65 €
Heat pump	9.531,92 €		9.531,92 €
Radiant floor	14.978,70 €		14.978,70 €
Max size PV plant	39.875,37 €		39.875,37 €
Battery 7kWh	6.690,00 €		6.690,00 €
Total			**120.598,93 €**
Replacement cost			
Description	**Cost**	**Discount rate coef.**	**Final value**
Replacement at 15 years	20.714,20 €	0,555264503	11.501,86 €
Residual value	-19.770,94 €	0,308318668	-6.095,75 €
Annual cost			
Description	**Cost**	**Present value factor**	**Final value**
Maintenance	1.068,66 €	17,29	18.479,26 €
Energy cost			
Description	**Cost**	**Present value factor**	**Final value**
Electricity	-988,00 €	17,29	-17.084,53 €
Global cost			
127.399,77 €			

Table 108. F5 scenario global cost

Results

The results are summarized in this paragraph. The coefficient used for the CO_2 is 0.46 $kgCO_2/kWh_{el}$.

Case	Global cost	Energy cost	kWh_{el}/year	kWh_{EP}/year	$kgCO_2$/year
A1	85.800 €	6.725 €	2270	5491	1044
A2	90.662 €	3.631 €	0	0	0
A3	92.925 €	2.784 €	0	0	0
A4	100.590 €	-13.332 €	-9827	-23781	-4520
A5	109.023 €	-15.303 €	-9827	-23781	-4520
B1	94.420 €	6.058 €	2112	5110	971
B2	100.496 €	3.372 €	0	0	0
B3	102.760 €	2.525 €	0	0	0
B4	109.698 €	-14.318 €	-10220	-24732	-4701
B5	118.149 €	-16.272 €	-10220	-24732	-4701

Table 109. Global cost summary results

Case	Global cost	Energy cost	kWh_{el}/year	kWh_{EP}/year	$kgCO_2$/year
C1	87.960 €	6.070 €	2114	5117	972
C2	92.729 €	3.424 €	0	0	0
C3	94.993 €	2.577 €	0	0	0
C4	103.279 €	-14.266 €	-10213	-24715	-4698
C5	111.730 €	-16.220 €	-10213	-24715	-4698
D1	97.711 €	5.727 €	1995	5082	917
D2	101.505 €	3.026 €	0	0	0
D3	103.751 €	2.162 €	0	0	0
D4	112.612 €	-15.027 €	-10512	-25439	-4836
D5	121.097 €	-16.946 €	-10512	-25439	-4836

Table 110. Global cost summary results

Case	Global cost	Energy cost	kWh_{el}/year	kWh_{EP}/year	$kgCO_2$/year
E1	92.893 €	5.549 €	1933	4678	889
E2	98.147 €	3.994 €	0	0	0
E3	100.462 €	3.199 €	0	0	0
E4	109.530 €	-14.456 €	-10667	-25814	-4907
E5	117.963 €	-16.427 €	-10667	-25814	-4907
F1	102.680 €	5.242 €	1826	4420	840
F2	107.256 €	3.683 €	0	0	0
F3	109.553 €	2.870 €	0	0	0
F4	118.949 €	-15.131 €	-10934	-26460	-5030
F5	127.400 €	-17.085 €	-10934	-26460	-5030

Table 111. Global cost summary results

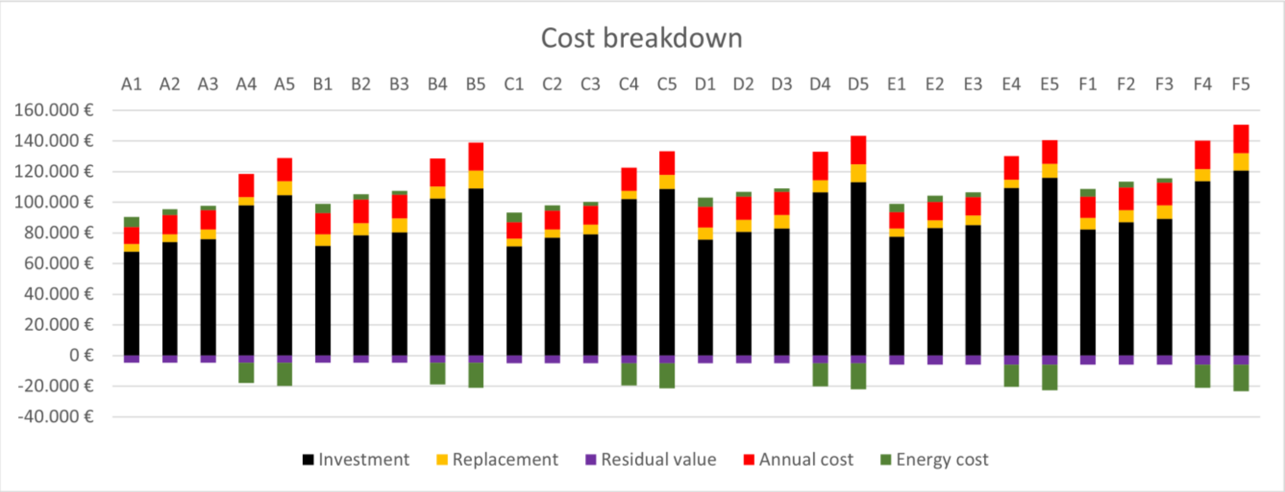


Figure 35. Cost breakdown chart

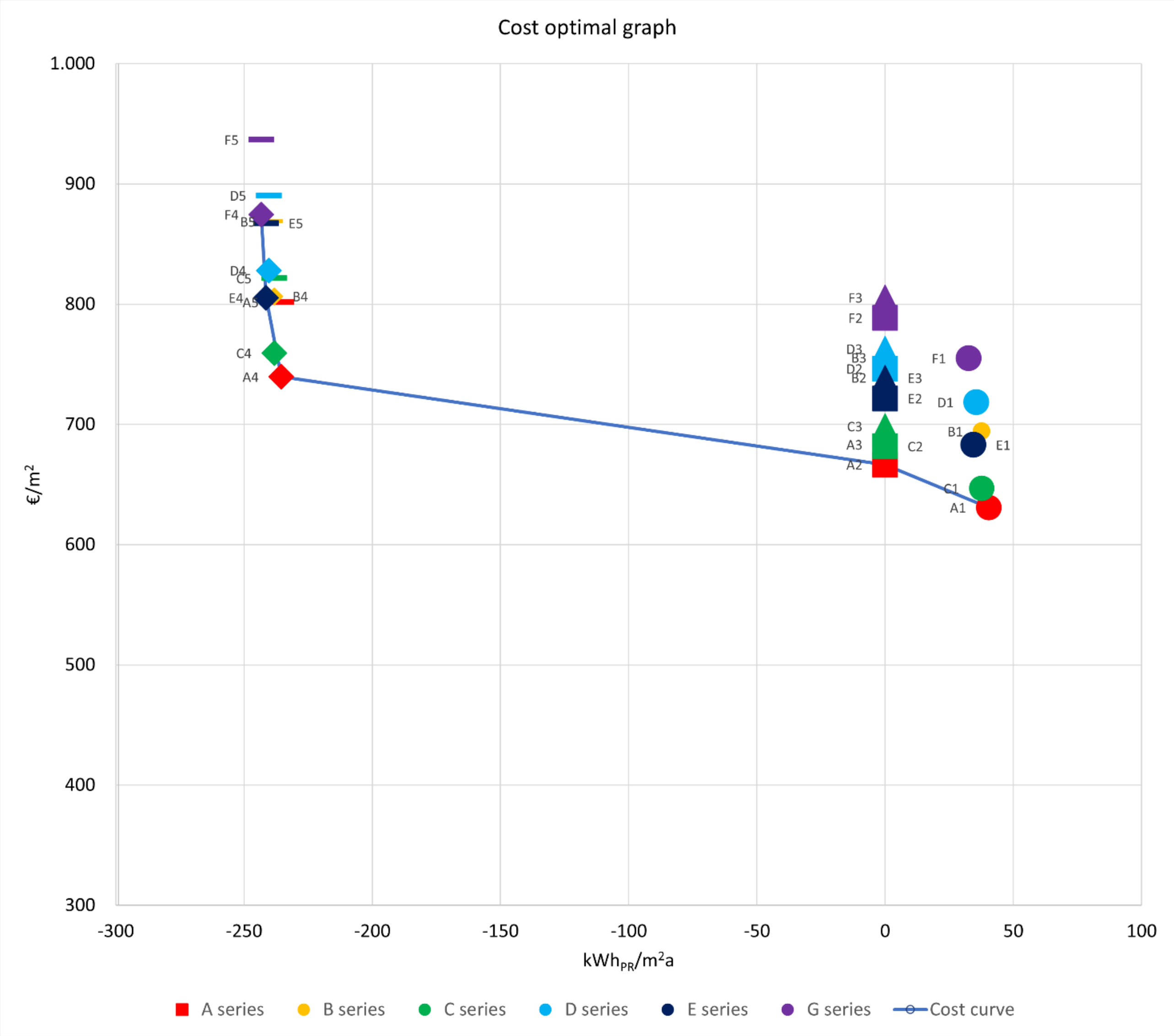


Figure 36. Chart with the global cost on vertical axis and primary energy on horizontal axis

The A series (with the legal minimum insulation, a PV plant that cover 60% of consumption and without the heat recuperator) is the one with the lowest global cost.

Sensitivity analysis

The calculation performed are based on parameters (discount rate, energy price, etc) that are based on estimation and they change with time and are difficult to predict. So it is interesting to calculate new global cost with different parameters to see if the best solution remains the same or not.

Real interest rate

The real interest rate applied was 4% as usual for construction work in Europe. By the way if the real interest rate was calculated with the actual (end 2023) market interest rate (R) and inflation value (Ri), it would be

$$R_R = \frac{R - R_i}{1 + R_i} = 0.95\%$$

The new global cost are

Case	Global cost	Energy cost	kWh_{el}/year	kWh_{EP}/year	$kgCO_2$/year
A1	90.885 €	10.108 €	2270	5491	1044
A2	94.989 €	5.458 €	0	0	0
A3	97.450 €	4.184 €	0	0	0
A4	97.850 €	-20.037 €	-9827	-23781	-4520
A5	107.380 €	-22.999 €	-9827	-23781	-4520
B1	102.072 €	9.106 €	2112	5110	971
B2	107.658 €	5.068 €	0	0	0
B3	110.119 €	3.794 €	0	0	0
B4	109.427 €	-21.518 €	-10220	-24732	-4701
B5	118.984 €	-24.455 €	-10220	-24732	-4701

Table 112. Global cost summary results with current discount rate

Case	Global cost	Energy cost	kWh_{el}/year	kWh_{EP}/year	$kgCO_2$/year
C1	91.899 €	9.123 €	2114	5117	972
C2	93.106 €	5.146 €	0	0	0
C3	94.943 €	3.872 €	0	0	0
C4	96.359 €	-21.440 €	-10213	-24715	-4698
C5	103.827 €	-24.377 €	-10213	-24715	-4698
D1	100.736 €	8.607 €	1995	5082	917
D2	103.152 €	4.548 €	0	0	0
D3	104.963 €	3.249 €	0	0	0
D4	106.872 €	-22.584 €	-10512	-25439	-4836
D5	114.392 €	-25.468 €	-10512	-25439	-4836

Table 113. Global cost summary results with current discount rate

Case	Global cost	Energy cost	kWh_{el}/year	kWh_{EP}/year	$kgCO_2$/year
E1	95.164 €	8.340 €	1933	4678	889
E2	100.320 €	6.003 €	0	0	0
E3	102.860 €	4.808 €	0	0	0
E4	104.184 €	-21.726 €	-10667	-25814	-4907
E5	113.715 €	-24.689 €	-10667	-25814	-4907
F1	107.762 €	7.879 €	1826	4420	840
F2	112.170 €	5.535 €	0	0	0
F3	114.683 €	4.314 €	0	0	0
F4	116.230 €	-22.740 €	-10934	-26460	-5030
F5	125.786 €	-25.676 €	-10934	-26460	-5030

Table 114. Global cost summary results with current discount rate

The global cost are higher for the solution without any PV plant installed and it get cheaper the more PV is installed. The cost difference between A1 and A4 is halved.

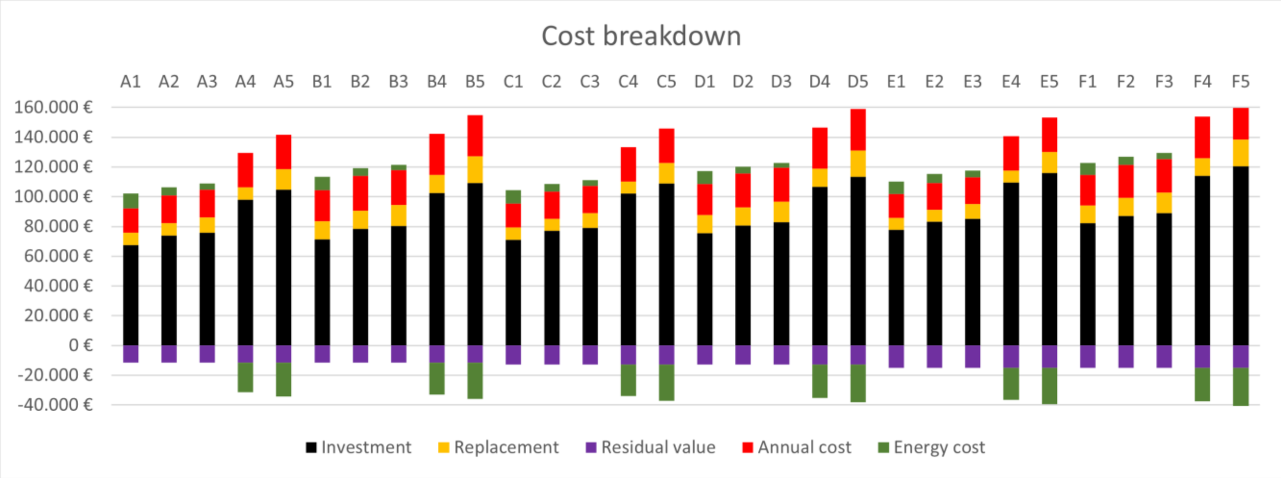


Figure 37. Global cost breakdown, current discount rate

Chart with the various cost item for all the cases

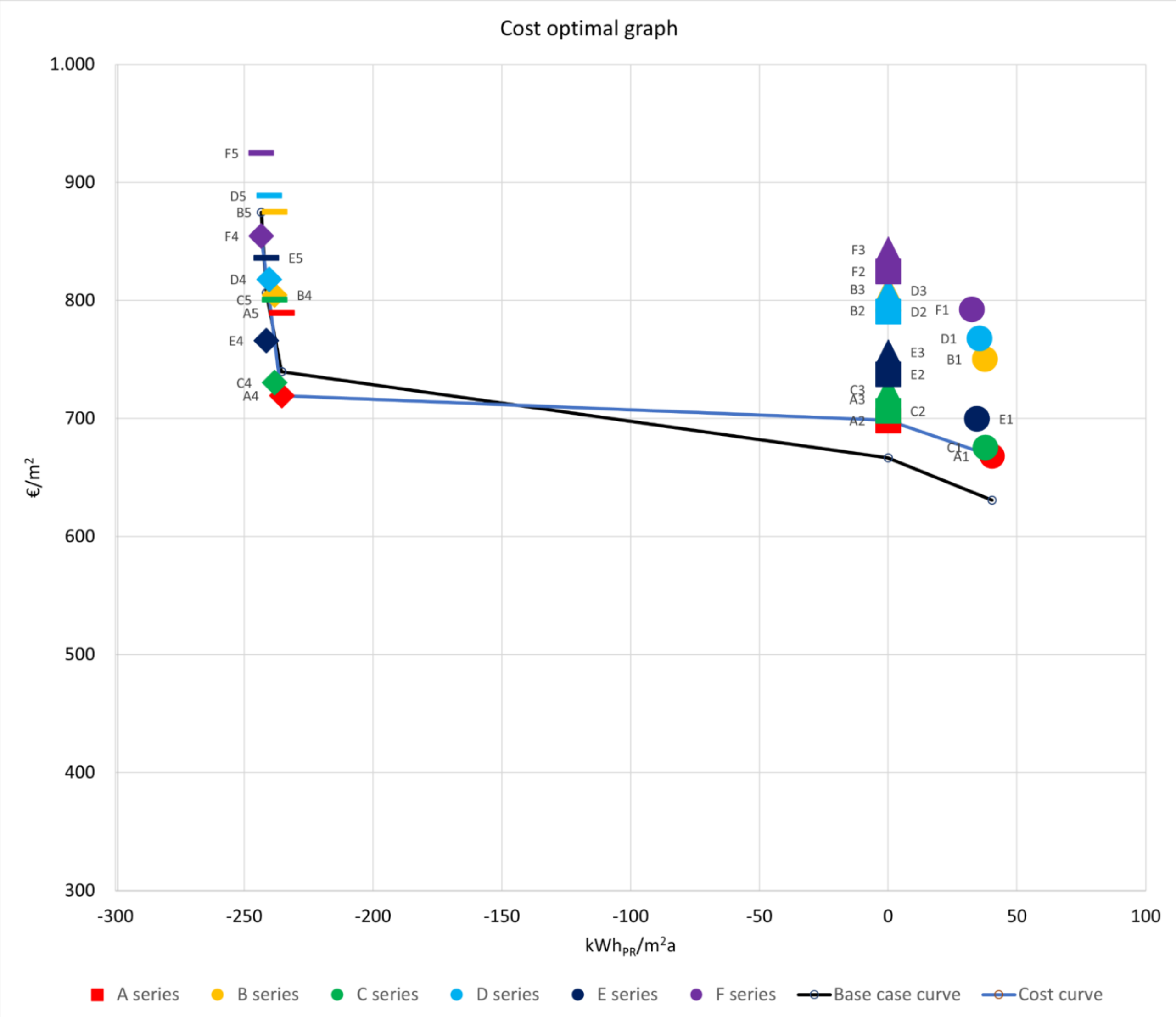


Figure 38. Chart with the global cost on vertical axis and primary energy on horizontal axis, current discount rate

Tax deduction

There is the possibility for the owner that do some renovation for a better energetic performance, to deduct the 65% or the 50% of the initial investment[41]. All the investment are deducted at 50% with exception of insulation panels, heat pumps and the radiant floor.

This scenario shows how much money the owner will spend, anyway all the savings of the owner are and expenditure for the State and so the citizens altogether.

Case	Global cost	Energy cost	kWh_{el}/year	kWh_{EP}/year	$kgCO_2$/year
A1	47.354 €	6.725 €	2270	5491	1044
A2	49.034 €	3.631 €	0	0	0
A3	50.297 €	2.784 €	0	0	0
A4	46.971 €	-13.332 €	-9827	-23781	-4520
A5	52.060 €	-15.303 €	-9827	-23781	-4520
B1	54.048 €	6.058 €	2112	5110	971
B2	56.622 €	3.372 €	0	0	0
B3	57.885 €	2.525 €	0	0	0
B4	53.833 €	-14.318 €	-10220	-24732	-4701
B5	58.939 €	-16.272 €	-10220	-24732	-4701

Table 115. Global cost summary results with tax deduction

Case	Global cost	Energy cost	kWh_{el}/year	kWh_{EP}/year	$kgCO_2$/year
C1	48.151 €	6.070 €	2114	5117	972
C2	49.956 €	3.424 €	0	0	0
C3	51.220 €	2.577 €	0	0	0
C4	47.976 €	-14.266 €	-10213	-24715	-4698
C5	53.082 €	-16.220 €	-10213	-24715	-4698
D1	55.655 €	5.727 €	1995	5082	917
D2	56.854 €	3.026 €	0	0	0
D3	58.100 €	2.162 €	0	0	0
D4	55.063 €	-15.027 €	-10512	-25439	-4836
D5	60.204 €	-16.946 €	-10512	-25439	-4836

Table 116. Global cost summary results with tax deduction

Case	Global cost	Energy cost	kWh_{el}/year	kWh_{EP}/year	$kgCO_2$/year
E1	50.178 €	5.549 €	1933	4678	889
E2	52.711 €	3.994 €	0	0	0
E3	54.026 €	3.199 €	0	0	0
E4	50.927 €	-14.456 €	-10667	-25814	-4907
E5	56.016 €	-16.427 €	-10667	-25814	-4907
F1	57.719 €	5.242 €	1826	4420	840
F2	59.843 €	3.683 €	0	0	0
F3	61.141 €	2.870 €	0	0	0
F4	58.100 €	-15.131 €	-10934	-26460	-5030
F5	63.206 €	-17.085 €	-10934	-26460	-5030

Table 117. Global cost summary results with tax deduction

Adding the bonus, the most convenient solution is the A4, and the second one is C4.

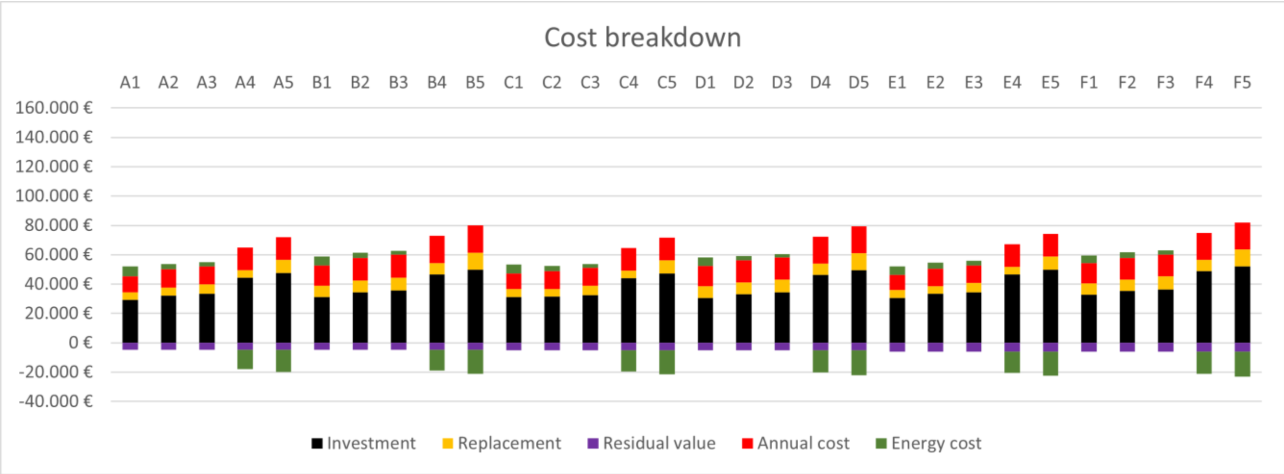


Figure 39. Global cost breakdown, tax deduction

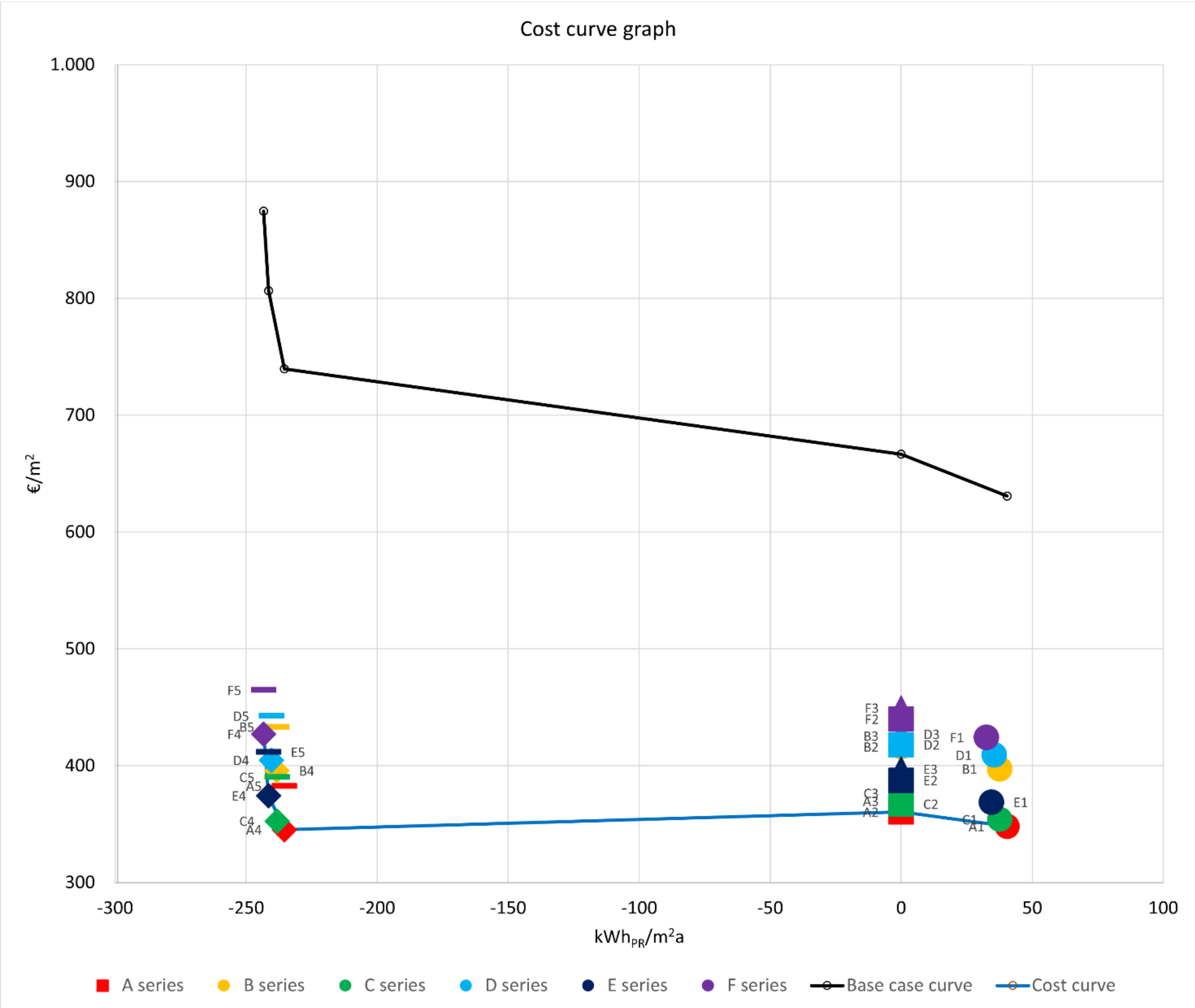


Figure 40. Chart with the global cost on vertical axis and primary energy on horizontal axis, tax deduction

Eco-cost

It is possible to give a price to the damage generated with ghg emissions, it is a theoretical price and it is not directly paid by anyone. In any case it is useful to completely evaluate the impact that any choice has on the environment and the eco system where we live.

The eco-cost of CO_2 is calculated with reference to the European guidelines[47] 20 euro/ton until 2025, 35€/ton until 2030 and then 50€/ton.

The only cases the emit are the one with a photovoltaic generation that only cover the 60% of the consumptions. The highest emissions are from the casa A1 that produces around 1 ton of CO_2 per year. Adding the eco-cost to the global cost means adding 800€, the cost is so small compared to the other items that doesn't change the best solution found with the base case scenario.

Discussion of the results

Considering the overall of the scenarios simulated with the sensitivity analysis, the best cases are the ones of the A series especially the A1 case. With the tax deduction the best case is the A4 (max size PV) and the second best is the A1 again. The results show that the legal minimum wall insulation is the best choice, and increasing the insulation doesn't pay off. With the heat pump heating, a reduction of 1kWh in the thermal need becomes less than 0.3 kWh of energy consumption, because the high COP of the system. This fact can explain why increasing the thermal insulation doesn't give better results when the global cost is evaluated.

The analysis for this thesis has been performed with reference to official data of the market or to price list released by the authorities. Anyway it is not possible to forget to mention that 2023, as the years after covid-19, are characterized by instable markets and geopolitical tension with two wars, in Ukraine and Israel, that involve some of the biggest oil and gas producers states. The price instability is also linked to other factors, in fact it is noteworthy that the prices (end of 2023) are more expensive than they should be because in the previous years it was available the bonus 110% that allowed people have their house renovated for free and this event started a speculation on material prices. According to some authors, the price raised between 50 and 100%[42].

Moreover, on December 2023 Chinese manufacturer were able to produce photovoltaic panels for as low as 0.15€/Wp[43]. When these panels will be supplied to Europe, the market for solar energy will be revolutionized, making the installation of PV system the winning choice to not only save money but also to earn it.

Considering all these elements, there is a strong probability that in two-three years, the building renovation scenarios described in this thesis, will have 30% reduction on the initial cost, spreading faster the ecological transition thanks to more convenient prices.

The last consideration is about the current laws that are already designed to push the citizens and house owners to best technical and economical solution, this explain why the best case found by this work is also the one that applies the rules and nothing more.

Conclusions

The first designing part of this thesis was about the thermal insulation of the building and it found some intrinsic limits: it is not possible eliminating some thermal bridges and the windows have bad orientation with only few of them south-oriented. Despite these problems, the wall insulation and the double and triple glazed windows halved the thermal need from 170 kWh/m^2 to 80 kWh/m^2.

The second part of the analysis was about finding the best plant to install, and this led to the combination of an A class heat pump and the radiant floor. This plant allows to have a uniform heating and to minimize the energy consumptions having the water with a relative low temperature compared to traditional systems. The analysis also discovered that solar thermal panels are nowadays obsolete compared to the photovoltaic systems. In fact the production of thermal energy results really low during winter when it’s needed and really high in summer; electricity generation solve this problem because it is possible to sell the energy surplus to the grid and moreover electricity can run multiple devices inside the house and it isn’t limited to thermal purposes.

During this study work, some parameters were easy to optimize, for example the best windows or the best insulation material, other choice weren’t easy to make and so the cost optimal analysis was applied on the remaining 30 scenarios.

The cost optimal analysis performed as prescribed by the European commission’s guidelines, brought to the best solution: the A1 case. The A1 case have: the legal minimum thermal insulation and the PV plant that covers the 60% of the consumption (as imposed by the law). In general thanks to the cost optimal analysis was possible to state that adding a battery to the PV plant doesn’t payback the extra investment and the same applies for the heat recuperator.

It is noteworthy that the best case is the one that follow the legal minimum and nothing more, this means that the rules are already designed to push the house-owners to the best solution. This fact is not always granted for all the laws that often are old and not updated to the new technology, but in this case EU makes a constant review of the EPBD directive once or twice a year, and also the Italian application has been revised in 2021, just two years ago.

The global cost for renovating the house into the best case found is 630 €/m^2 but making the market research for this analysis it was possible to notice that 2023 and more generally the post covid period, is characterized by economic instability and when this will end, in two-three years, the investment cost for the refurbishment will be lower and the ecological transition will be led by the Chinese convenient PV panels.

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