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Master Thesis

Retrofit of European Residential Building Stock: a bottom-up methodology to support large scale decisions

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NOMENCLATURE

Symbols

a	Solar absorptance [-]
c	Thermal Capacity [J/kg K]
d	Density [kg/m^3]
f(x)	Probability density function
k	Conductivity [W/m K]
n(i)	Counter of the output index I repetition
NV	Length of vector vv
N(x)	Counter of the x repetition
P(x)	Probability related to x
PI(i)	Probability related to output Index
R	Thermal resistance [m^2 K/W]
t	Thickness [m]
vv	Variable vector
X	Archetype
XX	Matrix containing all the archetype

Abbreviations

AF	Actualization factor
CES	Carbon Energy Savings
CI	Investment cost
CI_{PBT10}	Investment cost that verifies a PBT of 10 years.
$C_{O\&M}$	Cost of operation and maintenance
EBEE	Economic benefit due to the Environmental externality
EBES	Economic benefit due to the energy savings
EEMs	Energy Efficiency Measures
ES	Energy Savings
EPBD	Energy performance of buildings directive
HVAC	Heating, ventilating and air conditioning
LHS	Latin hypercube sampling
NB	Total Number of Buildings present in the real stock
NSM	Total Number of Buildings present in the Surrogate Model
NPV	Net Present value
PBT	Payback Time
PES	Primary Energy Savings
PEC	Primary Energy Consumption
PPS	Peak Power Savings
SA	Sensitivity Analysis
SV	Significant variables
SLABE	Simulation-Based Large-scale uncertainty/sensitivity Analysis of Building Energy performance

1 INTRODUCTION

The building sector in Europe accounts for approximately 40% of the total energy consumption and produces a share of 36% of the total CO_2 emissions in the EU [1]. Still, reducing the environmental impact of this sector is a challenge for two main reasons[2]:

- **Most of the buildings' stock is old**: more than 40% were built before 1960 and 90% before 1990, when legislations were either absent or less restrictive regarding the thermal property's requirement.
- **Low renewing rate**: only 1% a year of new buildings either replace this old stock or expand the total inventory.

For these reasons, the renovation of existing buildings becomes the focus of the European policy. Specifically, to increase the energy performance of buildings, the EU has established a legislative framework that includes the **Energy performance of buildings directive (EPBD) (2010/31/EU)**[3] and the **Energy efficiency directive (2012/27/EU)**[4]. Together, the guidelines promote policies that will help to (i) achieve a **highly energy-efficient and decarbonized building stock by 2050**, (ii) create a stable environment for investment decisions to be taken and (iii) enable consumers and businesses to make more informed choices for saving energy and money. As a direct consequence, **building stock modelling** has become an important topic since it represents a tool able to propose retrofit actions to accomplish the targets proposed by the directives.

1.1 State of Art

Over the last decades, different approaches to model a building category have been proposed[5],[6]. All the procedures can be reconducted to either a **Bottom-up** or **Top-Down** approach, as presented in Table 1. It is essential to highlight that, even if the results of the two procedures are the same, different paths are followed depending on the data available and the grade of accuracy required.

Table 1: Comparison between Top-down and Bottom-up model.

TYPE OF APPROACH	MAIN CHARACTERISTICS	LIMITS	TYPE OF SUB-MODEL	INPUT DATA REQUIREMENT	OUTPUT THAT THEY GENERATE	LIMITS
Top-down	It works at the aggregate level, focusing on the relation between the overall energy consumption and different input data.	The model parametrization is not carried out at end-user level	**Econometric** [7]	Economic and macroeconomic parameters (e.g., GDP)	Energy consumption throughout the regression method	It lacks details on current and future technological options
			Technological [8]	Technological data as technological progress, structural and architectural changes		It has no inherent capability to model discontinuous changes in technology
Bottom-up	Energy consumption is obtained by the aggregation of sub-systems' energy performance.	It required extensive databases of empirical data to support the description of each sub-system.	**Statistical** [9]	Energy performance as energy bills or measurement	Energy consumption throughout regression analysis	Does not provide detailed information on the end-use of Buildings (e.g., light, heating and cooling)
			Engineering [10]	Thermophysical parameters of the building stock	Energy consumption throughout heat transfer and thermodynamics calculations.	Detailed data because of a lot of thermophysical parameters involved

The **bottom-up model** with an **engineering approach** is further analysed because it permits to (i) develop a method that can give retrofitting options to the end-use, (ii) produce overall results regarding the building stock, (iii) enhance the accuracy of the results and (iv) confine the error dependency outside the algorithm through the exploitation of dynamic calculations. The latter peculiarity also permits to increase the accuracy of the result by only changing the input (and not the methodology), in case new and more accurate data will be available in the future.

The engineering approach can be further distinguished in Brute-force, Archetypes or Representative Buildings models as showed in Table 2.

Table 2: Different Engineering Bottom-up models.

TYPE OF ENGINEERING APPROACH	MAIN FEATURE	INPUT DATA REQUIREMENT	OUTPUT THAT THEY GENERATE	LIMITS
Brute-force [6]	Every single building of the stock is considered as an individual physical building model	Detailed and "real" data of every single building of the stock	Energy Consumption (EC) profile calculated as: $EC = \sum_{i=1}^{N} ED(i)$ However, the accuracy achieved by each method will be different.	Detailed data required may be not available.
Archetypes [11]	Building stock is divided into clusters. Each Cluster is represented by a Building archetype through a statistical combination of the average parameters.	The statistical distribution of the main parameters within the cluster to create the Archetypes.		The Statistical relations among the parameters that describe the buildings of the cluster may be not available.
Representative buildings [12]	Building stock is divided into clusters. Some "real buildings" are selected as representative of the average properties of the cluster.	A model with numerous Representative Buildings of the stock.		It is necessary to use a more significant number of representative buildings to have a reliable representation of the building stock because the high detailed information reduced the number of represented buildings.

The selection of one approach instead of another to produce a building stock model which can support the European directives is centred on the following trade-off:

- Achieving detailed input data to reduce the forecasting error of the stock's model;
- Develop a method that can be reproduced in all Europe with data currently available;

Therefore, Brute-force and Representative Buildings' models, although more accurate, cannot be used to support European or National policies as there is a current lack of detailed data for the European Territory. Whereas, **Archetype model** can be exploited at European scale because the lack of data is solved through the exploitation of statistical distribution.

An example of Engineering-Archetypes approach used to asses energy actions for the retrofitting of large-scale buildings Stock is the **SLABE** method, ' Simulation-Based Large-scale uncertainty/sensitivity Analysis of Building Energy performance', developed by [11]. The SLABE procedure can be divided into (i) Creation of the building stock model and (ii) Cost-Optimization of the model.

The *Creation of the building stock model* is represented schematically in Figure 1. The starting point is the average-archetype of the entire building stock; then, other archetypes are created by exploiting the statistical distribution of the variables which define the average archetype using a Monte Carlo method. Successively, sensitivity analysis (SA) is conducted to assess the dominant parameter and, eventually, to reduce the size of the model previously created. Finally, for each archetype produced, an "idf" file is created and run within the MLE+ program, which is a Matlab toolbox for co-simulation with the whole-building energy simulator EnergyPLus, to create the output indicators.

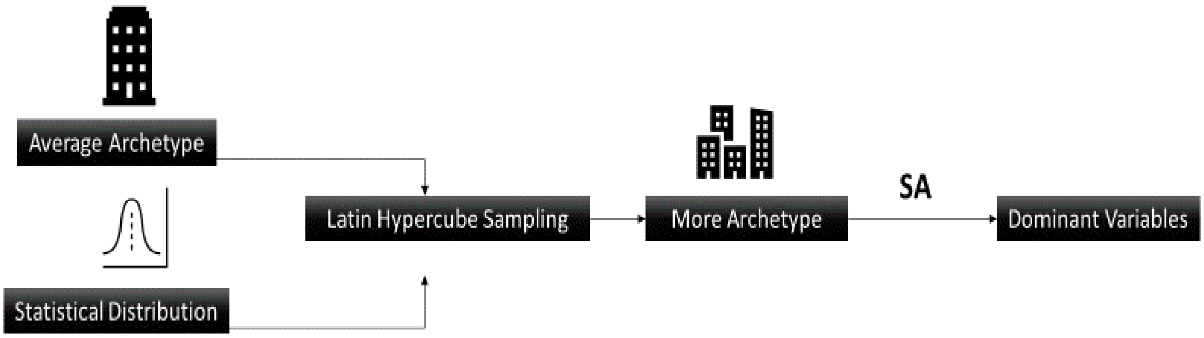


Figure 1: the creation of the building stock

The result of this first step is a distribution, which relates the value of the desired indicator (for example, Energy Demand ED) with the number of buildings present in the Stock, as shown in Figure 2.

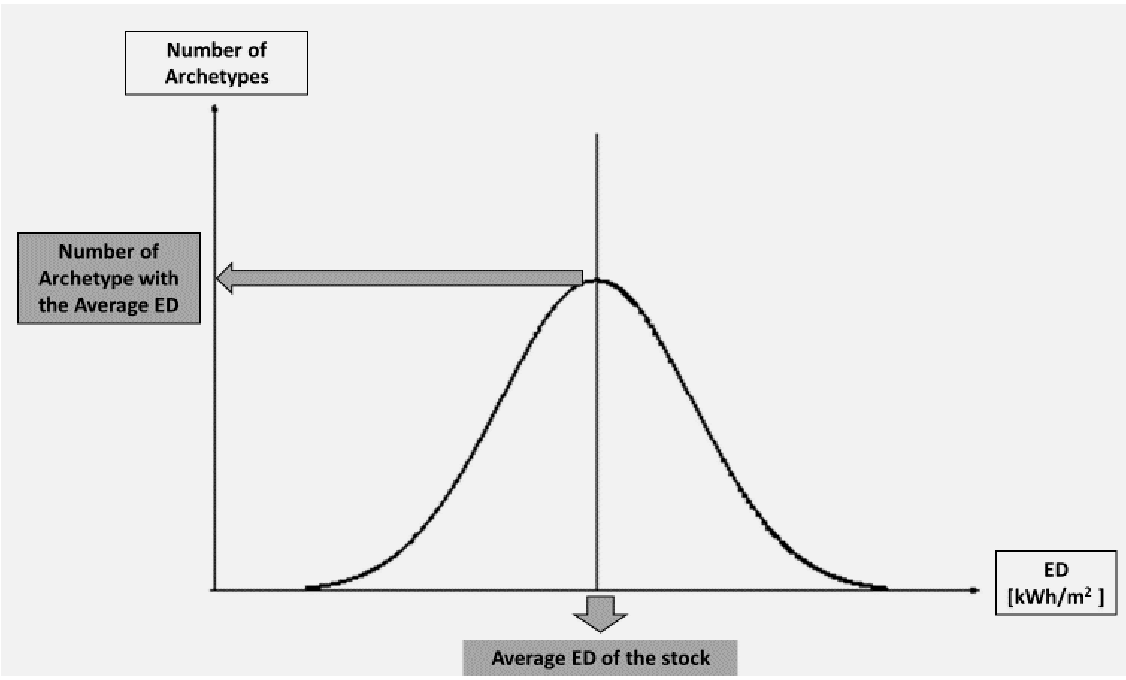


Figure 2: Example of the output of the model.

The Cost-optimization process, showed in Figure 3, proposes the best combination of Envelope, System and Primary Energy Consumption measures through a sequential approach. First, the Energy Efficiency Measures (EEMs) that most reduce the Energy Demand, the best combination of system measures (intended as the technologies used to supply the energy demand) and Primary Energy Consumption (PEC) are separately defined. In detail, the evaluation of the EEMs is done applying a sensitivity analysis on a new building stock which exploits the EEMs.

Secondly, the most effective EEMs and the best combination (HVAC+PEC) are sorted to create different combinations. Finally, the best retrofit package is defined as the combination that achieves the minimum Global Cost.

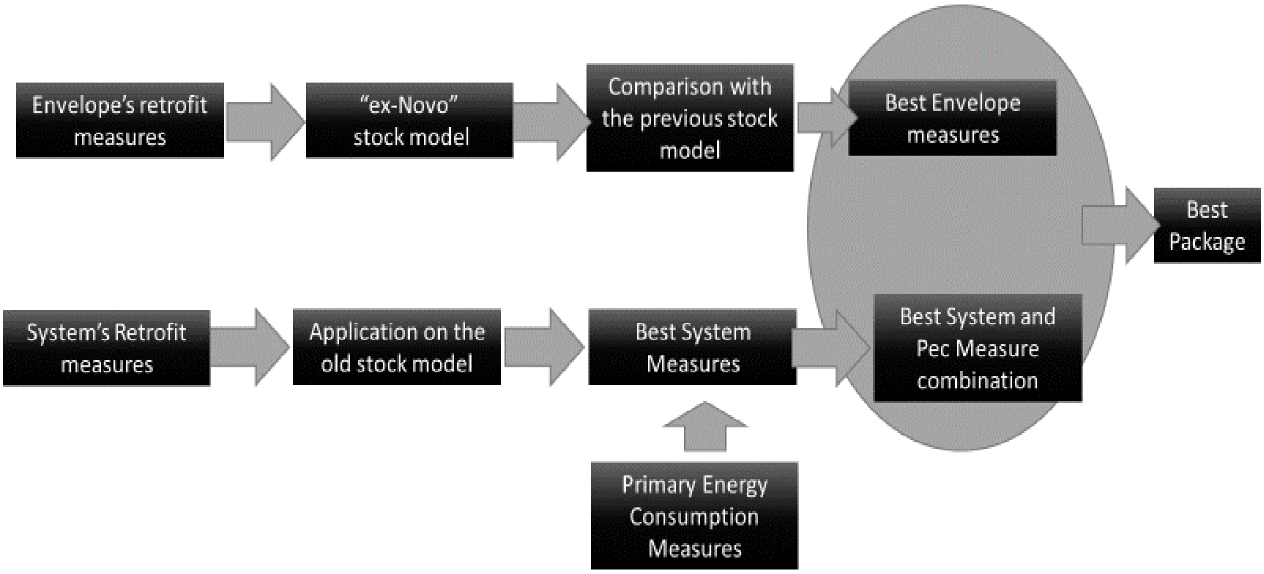


Figure 3: cost optimization procedure

The **Limitations** present in the SLABE method are:

1. It does not produce the surrogate model directly.
2. It does not predict a general rule for the number of archetypes required to model the existing stock.
3. The retrofit involves the creation of an 'ex-Novo' model, where the archetypes do not represent the retrofitted version of the ones previously modelized but are statistically produced.

Point (1) leads to a time-consuming program which can create the surrogate model only after having produced the complete result through a sensitivity analysis study. Thus, it is not worth creating the surrogate model as the already existing model is more accurate.

Point (2) produces a difficult application of the methodology since the user cannot relate the uncertainty of the stock model to the number of archetypes created whatever the category and the number of independent variables.

Point (3) produces results able to track the effects of the retrofit proposed only at the stock level because the archetypes of the 'ex-Novo' stock are not produced by directly retrofitting the archetypes of the previous stock. Thus, it is not possible to understand how each building of the stock responds to the retrofit solution because there is no direct correspondence between the single archetypes of the two models.

1.2 Objectives and Novelty

Objectives

The Intended aim is to propose retrofit actions able to accomplish large scale targets, like the ones of the European Directives, through a methodology able to produce information about the economic and technical effects of these measures at building and stock level with the data currently available. In this way, the policymaker can define whether is more convenient to apply the proposed measure on all the buildings or just on a portion of the entire stock.

Novelty

The presented research presents the following novelties compared to the existing state of the art:

1. Development of a method that directly produces the surrogate model with the minimum number of Archetypes of the Existent building stock;
2. Development of a method that allows the user to relate the number of archetypes with the final accuracy of the surrogate model;
3. Basing the retrofit on the Existent Building stock instead of creating an "ex-Novo" stock: the archetypes of the surrogate model (previously created) are directly retrofitted starting from the less efficient ones and proceeding forward until the retrofit is convenient. In this way, as there will be a direct correspondence between the archetype of the Inefficient and Retrofitted stock, the methodology can record the results of the measure also at buildings' level.

2 METHODOLOGY

In the methodology section it will be explained in detail how the existing building stock model is obtained and how its retrofit is achieved.

2.1 Model of the Building stock

To assess a methodology able to produce large-scale results the availability of a large-scale database is required. Regarding this, TABULA database [13], developed by Intelligent Energy Europe program (IEE) [14] to offer comprehensive and harmonized data regarding the EU's building stock, can be used as a starting point. Concerning the approach, the Archetype-Engineer one is selected because it permits to obtain results also when detailed data are not available, according to what has been exposed in the state of art section 1.1.
Overall, the creation of the surrogate stock model is based on the following steps:

1. **Data collection:** First, the building category is defined in terms of end-use (Residential or Commercial), number of buildings and construction year. Secondly, buildings' information is collected using both TABULA and local database in order to identify (i) the variables that will be used to define a generic Archetype, (ii) the variables' variation range and (iii) which discrete values can be assumed by the variables. Finally, the Average Archetype of the category is defined.
2. **Sensitivity analysis:** The variables of the average archetype model are variated one by one within their range. Thus, dominant input variables are identified by recording the variation obtained in the output.
3. **Archetype Production:** A probability distribution is associated with each dominant input variables. Then, other archetypes beyond the average one are created by combining the discrete values of these variables statistically.
4. **Model size definition:** Each time a new archetype is created, the error related to the changes in the output results is evaluated. Therefore, when the addition of a new archetype to the model produces an error minor than the threshold assumed, the minimum size is reached.

2.1.1 Data Collection

First step: Category definition

Thermophysical buildings stock information is required to divide the utter stock into different clusters. Under the assumption that there is a direct correspondence between the year of construction and thermophysical properties, the division in categories of the stock can be done by relating the buildings with their construction year.

Some periods of construction should be avoided to create a comprehensive methodology:

- *Before 40'*: buildings built before the second world war are often considered as historical, which cause different restrictions during the retrofit moment.
- *After 80'*: the legislation started to produce laws which enhanced the efficiency of the buildings.

For these reasons, the methodology focuses on buildings built between 40' and 80'.

Successively, it must be decided in how many clusters these building should be divided. Without specific information, the division into clusters can directly follow the one done by TABULA since it already gives the average archetype for each proposed category. In specific, TABULA's framework divides the buildings into categories at National scale and links an "archetypes building" to each of them with average geometrical and thermo-physical characteristics.

Second step: Variable Definition

As [12] exposes, variables required to define an archetype model can be grouped into:

- **Operation**: Location, Schedules, plug and process load, lighting densities, ventilation needs, occupancy,[...];
- **Form**: total floor area, number of floors, orientation, aspect ratio, shading, [...];
- **System:** HVAC system types, Component efficiency, Control settings, lighting fixtures and Daylight control, [...];
- **Envelope**: Exterior wall, roof and floor, transparent elements, interior partitions, internal mass, [...];

The quantity of these variables must be optimized to meet an optimum trade-off between the computational time and the accuracy of the method. Indeed, it must be noticed that increasing the number of parameters that describe the Building model leads the computational time of the model to grow because the Archetype will represent (even though more accurately) a lower amount of buildings.

Successively, the selected variables must be characterized in terms of *Discrete values* and *Range*. Indeed, as variables cannot variate in the continuous field, discrete values must be defined within a range and variation-steps technologically acceptable.
Figure 4 schematically explains the Variables definition moment.

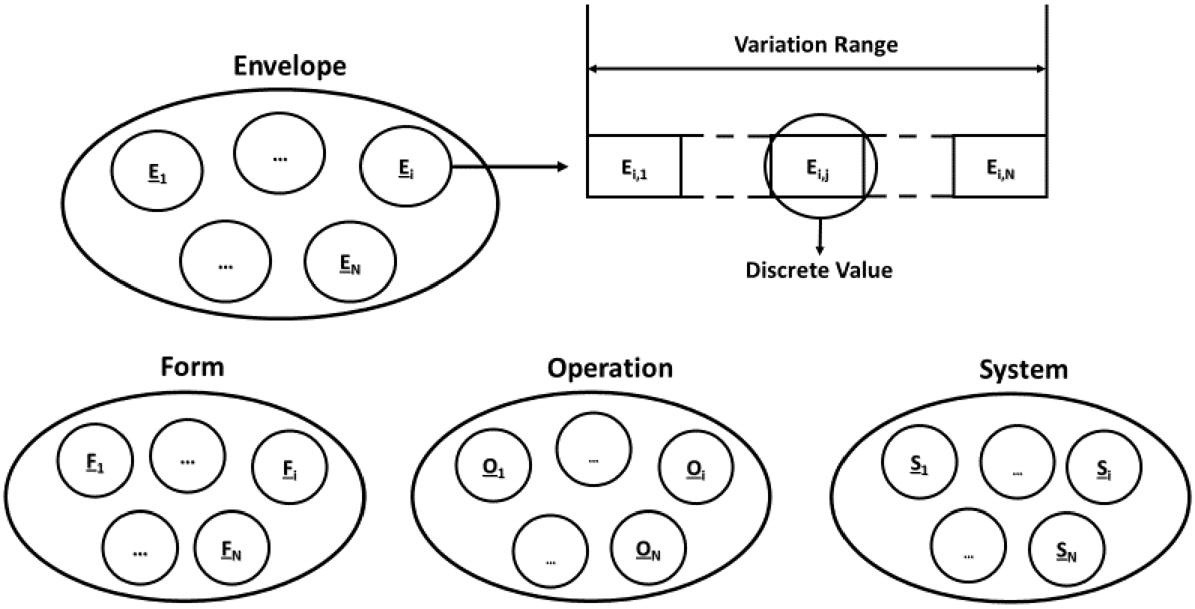


Figure 4: Variables definition.

Third step: Average Archetype

By the moment that the average archetype presented by TABULA database only covers:

- Form
- Transmittance
- General construction information

Its model should be improved by including secondary data for the building stock analysed. Specifically, the information provided for the Average Archetype of each cluster category proposed by TABULA can be further developed in the following way:

- Operation: Standard schedule, experience;
- Form: TABULA;
- System: TABULA, Standard schedule and expertise;
- Envelope: experience and by imposing congruence between the general construction stratigraphy and the Transmittance data;

2.1.2 Sensitivity Analysis

The size of the model, as [11] pointed out, depends on the number of variables that are variated to produce the archetypes. Thus, it is essential to accurately define how many variables variate to produce a reliable stock model with the minimum size. For this reason, this methodology is chosen to set these variables equal to the significant input variables obtained from the Sensitivity Analysis'(SA) results. Specifically, in the SA, the variables which describe the average archetype model are variated one by one within their range. Finally, the parameter whose variation more affects the output will be individuated and defined as significant variables (SV). Figure 5 schematically explains the SA moment.

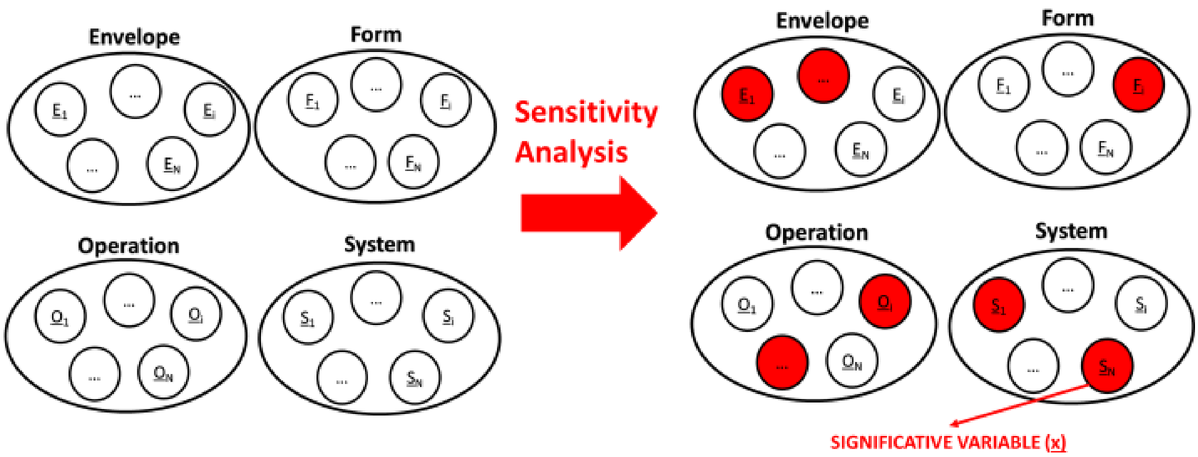


Figure 5: Sensitivity Analysis, identification of the significant variables (in red).

2.1.3 Archetypes production

As stipulated by the Energy Performance of Building Directive, the Average Archetype by itself cannot be representative of the stock since the members of one building category provide different energy performances. To overlap this limitation, it is necessary to model other archetypes beyond the average one.

Analytically, to define an Archetype means to select a value for each of the form, system, envelope and operation variables previously defined. In this methodology, with the intent of reducing the model's size, the definition of the model's archetypes consists of the selection of a discrete value for only the dominant variables, while the other variables will be handled equally to their average values.

The *first step* is to assess what is the probability that an archetype manifests a specific discrete value x of the generic significant variable x̲. For this reason, a probability density function f(x) is produced, where the higher f(x) is, the higher is the probability that the archetype presents the discrete value x of the significant variable x̲. The step is schematically explained in Figure 6.

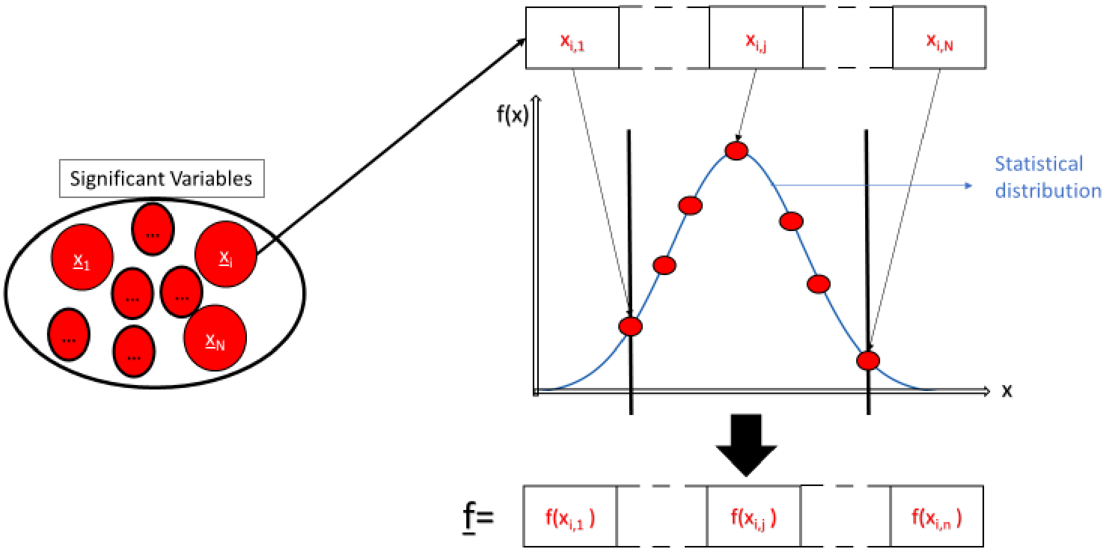


Figure 6: Archetypes production, assignment of the probability density f(x).

In the **second step** illustrated in Figure 7, a specific discrete value x_j for each significant variable x̲ is selected according to its probability $P(x_j)$ defined as :

Equation 1: Evaluation of the probability that a significant variable x̲ present the value x_j.

$$P(x_j) = \frac{f(x_j)}{\sum_{j=1}^{n} f(x_j)}$$

Consequently, a vector vv̲ is created by repeating each x_j $N(x_j)$ times, where $N(x_j)$ is defined as

Equation 2: Number of time N that the value x_j is repeated within the vector vv̲.

$$N(x_j) = P(x_j) * NV$$

In this way, by deciding an index randomly from 1 to NV, it is possible to select a value x_j=vv̲(index) according to its probability $P(x_j)$.

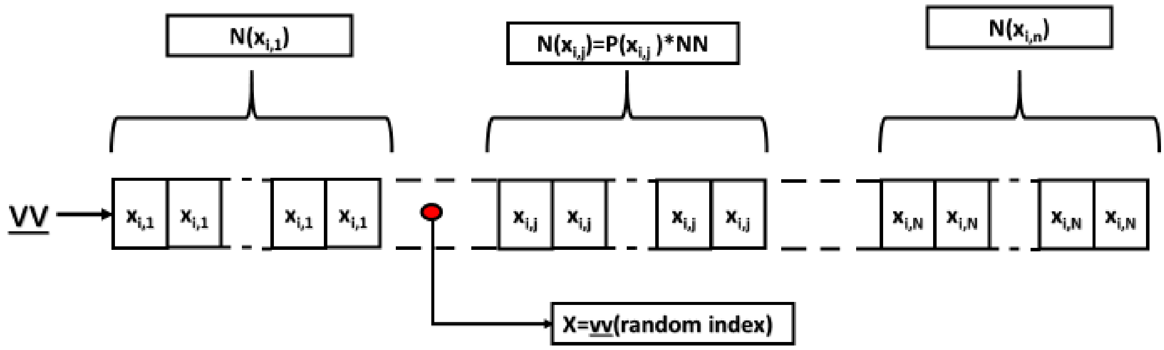


Figure 7: Archetypes production, the configuration of the vector vv

The procedure needs to be repeated in order to create different vectors vv for each significant variable. Hence, the archetype **X** is defined by selecting a discrete value x_j along with each vector vv and will be collected in the matrix **XX,** as Figure 8 explains.

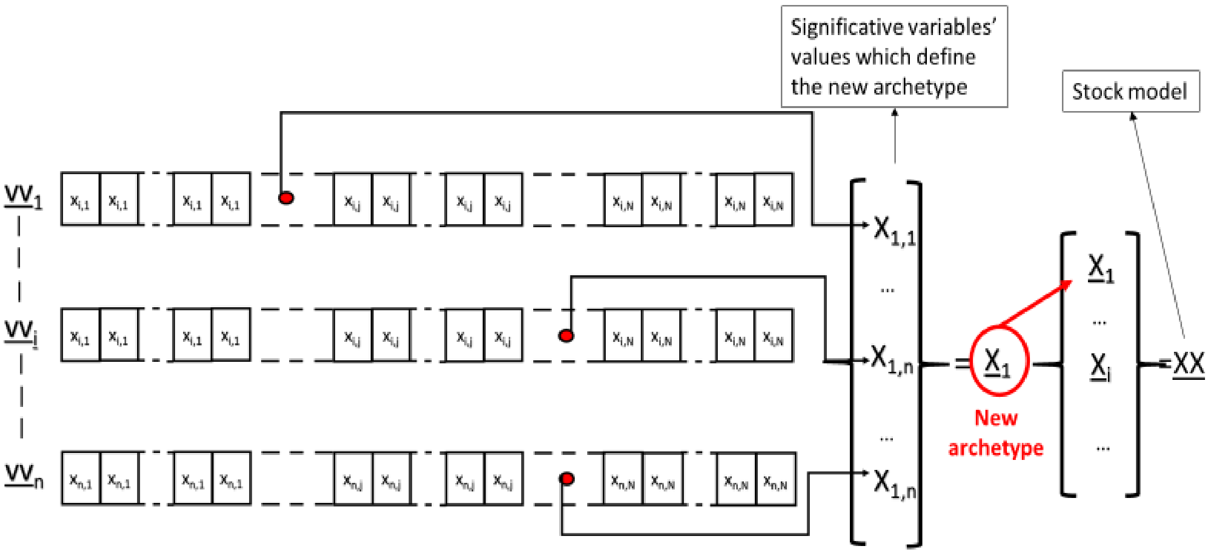


Figure 8: Archetypes production.

2.1.4 Model size definition

The Model size definition answers the question "How many archetypes **X** should be contained in the matrix **XX**?".

Theoretically, the Stock model size can be equal to the total number of Buildings NB present in the stock. However, to run the simulation for such a high amount of archetypes can be both time-consuming and not necessary when the stock is about the city scale, and variables do not follow a random distribution. Indeed, as the variables follow a statistical distribution, the histogram obtained by grouping the output index of each MLE+ simulation will tend to assume a specific shape for n[1] tending to NB. Therefore, a minimum number of archetypes NSM can be defined as the number which allows reproducing a distribution with a shape similar to the one that is obtained if n would be equal to NB. Consequently, uncertainty considerations are carried out to evaluate "how much the shape of the output distribution has changed after the current iteration", following the procedure showed in Figure 9. Specifically, the error related to the shape of the output distribution is analytically defined as:

Equation 3 Definition of the error related to the new distribution's shape.

$$error(i) = \frac{||PI(i) - PI(i-1)||}{||PI(i)||}$$

where the PI is the probability vector which defines what the probability that the next output index "I(Xi)" will fall in a specific range of the histogram is. Analytically, the probability PI_j that the output index will be contained within the range j of the histogram is equal to :

Equation 4 Probability that the new index is contained within the range n_j.

$$PI_j = \frac{n_j}{\sum_{j=1}^{n} n_j}$$

Where n_j counts the number of time that an output index produced has had a value contained within the range j across the iterations from 1 to i.

[1] Number of Archetypes present in the model

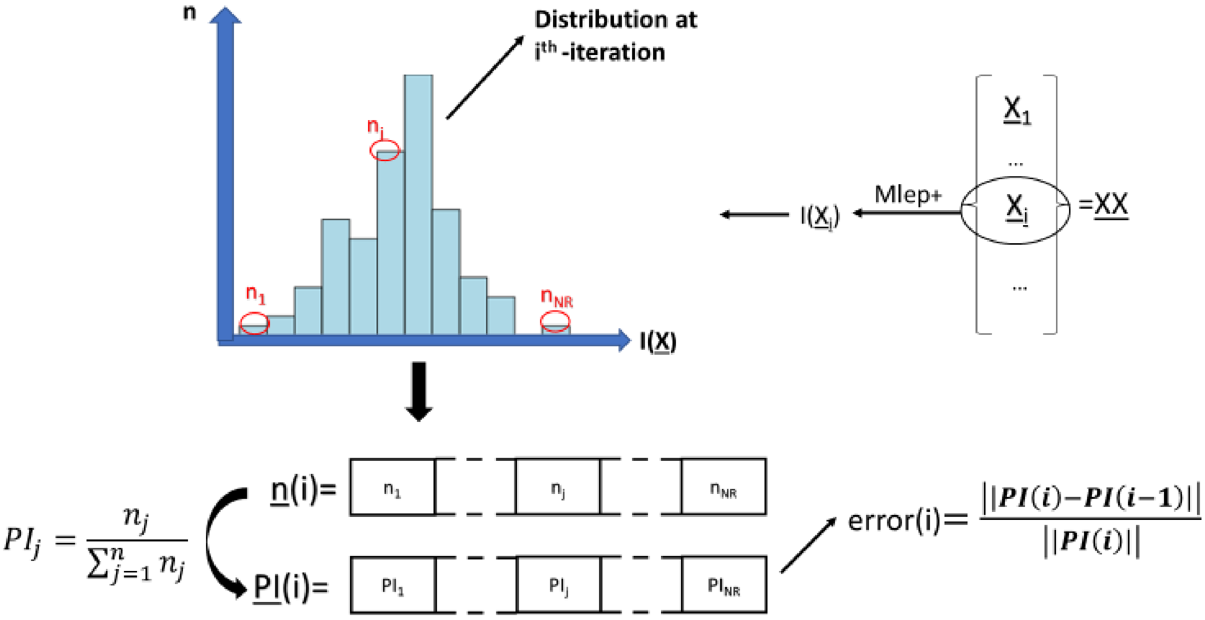


Figure 9: Archetypes production, the error evaluation procedure.

Therefore, the minimum size NSM is reached when the error(i) goes below the prefixed threshold and the matrix XX, containing all the archetypes created during the NSM iteration, represents the (surrogate) Building stock model as explained in Figure 10.

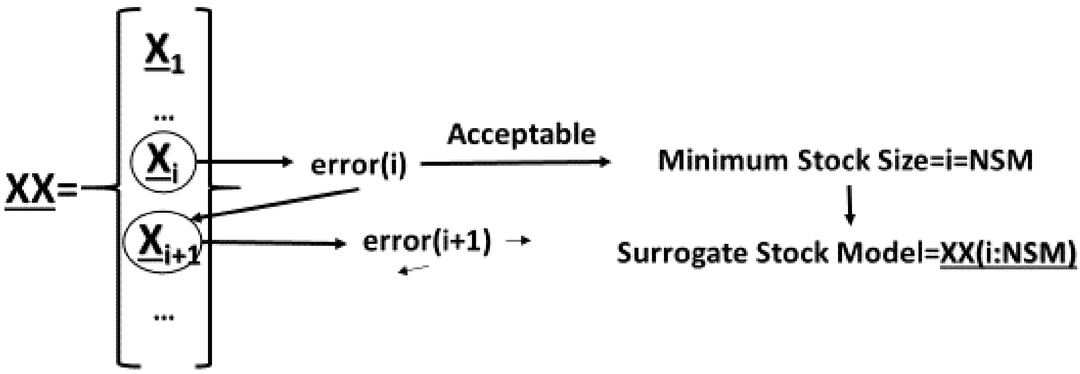


Figure 10: Archetypes production, the definition of the minimum size and the (surrogate) stock model.

Finally, the distributions of $I(X_i)$ obtained with NSM archetypes need to be related to the one that would be achieved with NB archetypes.

Under the assumption that these two distributions have the same shape, this last step is done by redefining the n vector as:

Equation 5: Scaling to NB archetype.

$$n(j) = NB * PI(j)$$

In other words, the distribution obtained with the surrogate model is multiplied for the constant NB/NSM.

2.2 Retrofit of the Existent Building Stock

The model composed by NMS archetypes, which represents the existent stock, is successively retrofitted. In general, retrofit solutions can be selected following two different approaches:

- *Parametric Analysis* [15]*:* Each technology is analysed as stand-alone, exploring different configurations and highlighting the technological and economic impact of them. As a conclusion of this method, the analysis indicates, for each technology, what the best configuration is.
- *Integrated optimization analysis* [16]: the method explores a combination of all the technologies proposed. In the end, through an optimization algorithm, it is defined which technologies' combination is the best.

However, whatever the approach, the method used to analyse the effects that one technology or a combination of technologies have on the stock can be the same.
Therefore, the method proposed will focus on how to investigate the effects of a general retrofit solution on the stock.

2.2.1 Indicators

Indicators are required to record and quantify the effect of a retrofit solution. The indicators selected in this methodology can be divided into two categories:

- *Economic Indicators*: aim to quantify the economic benefit generated by the retrofit solution;
- *Technological Indicators*: aim to quantify the solution's efficiency in terms of energy, power and CO_2 savings.

Concerning the ***Economic Indicators***, the first one calculated is the Net Present Value (NPV), where the actualized economic revenue produced along the life-span τ of a technology j is depurated from the initial Investment Cost (CI). Therefore, a positive NPV is essential for assessing the economic convenience of the solution. The Equation below reports the general form of the NPV function where the net economic revenue produced each i^th-year is evaluated as the difference between the Economic Benefit due to the Energy Saving (EBES) and the cost due to the Operation and maintenance $C_{O\&M}$. Specifically, the Energy Saving (ES) associated with a generic energy vector is multiplied for its market cost. Finally, the net revenue produced each i^th-year is actualized to the investment moment through the Actualization Factor R(i).

Equation 6: Evaluation of the Net Present Value.

$$NPV = \sum_j \left(-CI(j) + \sum_i^{\tau} AF(i) \cdot (EBES_i(j) - C_{O\&M,i}(j)) \right)$$

Equation 7: Actualization factor.

$$AF(i) = \left(\frac{1}{1 + (discount - inflaction)} \right)^i$$

Equation 8: Economic Benefits due to the Energy Savings

$$EBES_i = \sum_i^n EnergySavings_i \cdot C_i$$

Considering that the building retrofit is contained within the framework of the climate change supporting directives, the NPV can be further enriched by including the Economic Benefit due to the Environmental Externality (EBEE), which otherwise has to be sustained entirely by the government as a social cost. In that case, the expression of the NPV will become:

Equation 9 Net Present Value Considering the Economic Benefit due to the Environmental Externality

$$NPV = \sum_j (-CI(j) + \sum_i^{\tau} AF(i) \cdot (EBES_i(j) + EBEE_i(j) - C_{O\&M,i}(j)))$$

To assess a value to that externality, different approaches have been utilized in the literature over the past years. For example, the paper [17] utilized the opportunity cost method and a time series analysis to forecast future values; whereas [18] utilized the Life Cycle Assessment (LCA) methodology to forecast the economic impact of the environmental externality in terms of $/km and then evaluate two different vehicles.

As a critical comment of the literature review, it must be pointed out that the most comprehensive and accepted approach among the scientific community is the one that estimates the economic impact of the environmental externality through an LCA study. However, the data required to conduct the LCA are, in many cases, unavailable. This leads in some cases to the use of not adequate data from environmental databases as Ecoinvent [19], causing that the information obtained does not have reliability in absolute terms. Thus, the

LCA's results can be used only in relative terms to make a comparison with another technology which share the same function.

Because of that, the assessment of the environmental externality's cost using the LCA methodology is still a field to be included in the Buildings retrofit analysis. Indeed, buildings retrofit usually involves more than two technologies whose final function may not be the same, making the relative comparison either unworkable or extremely time-consuming due to the massive amount of data required because an LCA has to be assessed for each technology.

To overcome this limitation, according to the carbon tax idea developed by the US government, a possibility is to assess the Social Carbon Cost in terms of unit cost per unit of CO_2 emitted, equal for all the technologies. Therefore, the EBEE can be expressed as:

Equation 10: Economic Benefit due to the Environmental Externality

$$EBEE = CO_{2\ eq,saved} * C_{tCO2}$$

As a support of the information given by the NPV, also the Payback Time (PBT) is evaluated as the lifetime τ that verifies an NPV equal to zero :

Equation 11 Simple Payback time

$$Simple\ PBT = \frac{Investment\ Cost}{EBES}$$

Equation 12 Payback Time

$$PBT = log_{(1+i)} * (\frac{EBES}{EBES - CI * i})$$

Equation 13 Payback Time considering the Economic Benefit due to the Environmental Externality

$$PBT\ with\ Externality = log_{(1+i)} * (\frac{EBES + EBEE}{(EBES + EBEE) - CI * i})$$

Finally, the Incentives that the government should give to the private sector to ensure a PBT equal to 10 years are estimated as:

Equation 14 Evaluation of the Incentives

$$Incentives = CI - CI_{PBT10}$$

Where CI_{PBT10} is the investment cost needed to verify a PBT of 10 years and calculated as:

Equation 15 Evaluation of the CI_{PBT10}

$$CI_{PBT10} = EBES * \frac{(1+i)^{PBT} - 1}{i * (1+i)^{PBT}}$$

Beyond the economic indicator, ***technical indicators*** are defined to evaluate the change of performances obtained with the solution proposed. For this reason, the following indicators are evaluated:

- *Primary Energy Savings* (PES) evaluated as the difference between the Primary energy required by the existing stock and the one required by the retrofitted stock:

Equation 16 : Primary Energy Savings

$$PES = PE_{existing} - PE_{retrofitted}$$

- *Peak Power Savings* (PPS) evaluated as the difference between the Peak Power required by the existing stock and the one required by the retrofitted stock:

Equation 17: Peak Power Savings

$$PPS = PP_{existing} - PPS_{retrofitted}$$

- *Carbon Emissions Savings* (CES) evaluated as the difference between the CO_2 emissions of the existing stock and the ones of the retrofitted stock:

Equation 18: Carbon Emictions Savings

$$CES = CE_{existing} - CE_{retrofitted}$$

2.2.2 Procedure for Synthetic Presentation of the Results

The general aim of the retrofit procedure is to evaluate the technological and economic impact that the measures have on each archetype of the surrogate stock model.

First, the archetypes which composed the surrogate stock model are sorted based on their initial energy demand, in a decreasing way. Then, starting from the archetype with the highest energy demand and proceeding forward, the retrofit solution is applied to each archetype and the value of the different indicators is recorded.

Once obtained the indicators' value for each archetype of the model, the information has to be organized in a single graph and related to the initial ED. For this reason, as shown in Figure 11, the progressive cumulate of a general indicator is reported:

Equation 19: Evaluation of the cumulate value when j archetypes have been retrofitted.

$$Cumulate(j) = \sum_{i=1}^{j} Indicator_i$$

Where j is the current archetype retrofitted.

This presentation method particularly fits with the information sought by the policymaker because it shows how the global effect of the solution changes by modifying the number of retrofitted buildings. In other terms, the figure shows the cumulative impact of the retrofit measure with a retrofitted fraction of the stock discretely variating from 0 (none of the archetypes retrofitted) to 1 (all the stock retrofitted).

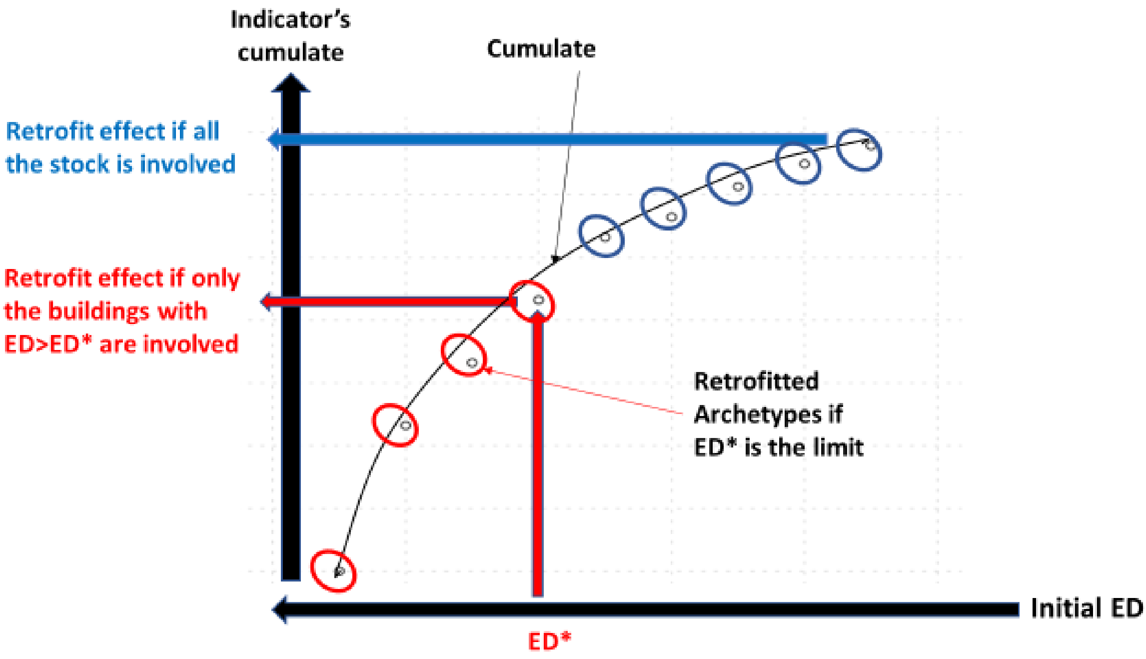


Figure 11 Layout of the main output figures

Moreover, as shown in Figure 12, from the cumulate shape the effect of the retrofit measure on the single archetypes can be understood. Indeed:

- a positive derivate means that the indicator assumes positive values for the buildings;
- a decreasing slope of the curve means that the indicator assumes gradually decreasing values as the initial ED of the building decrease.

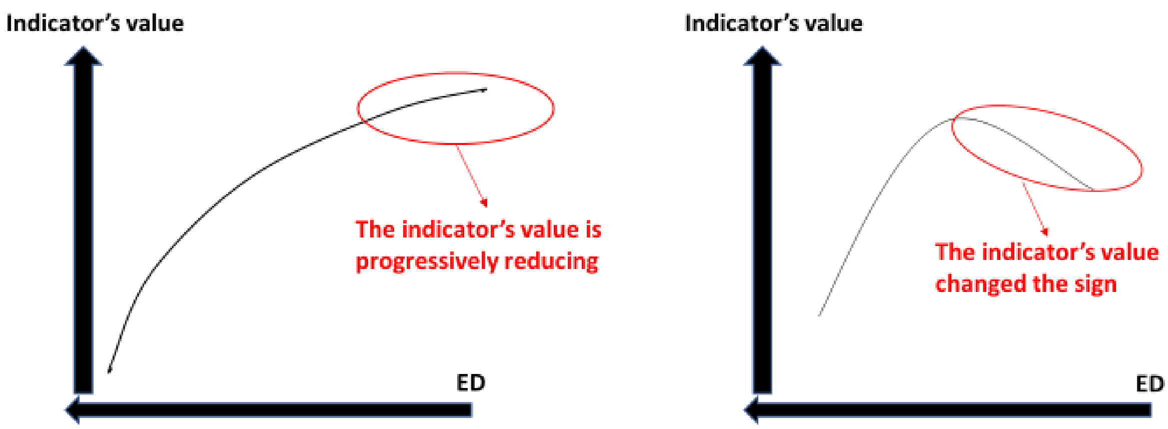


Figure 12 Explanation of the Cumulate shape

3 CASE STUDY

The methodology exposed in chapter 2 has been used to assess the retrofit of Barcelona's residential building stock, focusing the attention on all the residential buildings constructed between 1960 and 1980.

3.1 Software

Different types of software have been used to achieve this analysis. The specific software applications used to reproduce the methodology are:

- **SketchUp**

SketchUp [20] is a computer graphics application for 3D modelling oriented towards architectural design, urban planning and civil engineering. SketchUp has been used to produce the architectonical model of the average archetype previously defined in the methodology.

- **OpenStudio**

OpenStudio® [21] is a collection of software tools to support whole building energy modelling using EnergyPlus. Across the case study, the open studio is used to define the thermophysical proprieties to the average archetype's envelope such as the stratigraphy, thermal zone and materials properties. As a result, OpenStudio produces an idf file that can be successively read by EnergyPlus.

- **EnergyPlus**

EnergyPlus™[22], [23] is a whole building energy simulation program that engineers, architects, and researchers use to model both energy consumption—for heating, cooling, ventilation, lighting and plug and process loads—and water use in buildings.

The idf file previously created within the OpenStudio Environment is further developed with EnergyPlus to add (i) the operational parameters such as Location, Schedules, plug and process load, lighting densities, ventilation needs, occupancy; and (ii) the System Parameters like HCVAC system types, Component efficiency, Control settings, lighting fixtures, and Daylight control.

- **Matlab**

MATLAB [24] is an environment for numerical calculation and statistical analysis written in C, which also includes the programming language of the same name created by MathWorks. MATLAB allows the users to manipulate matrices, display functions and data, implement algorithms, create user interfaces, and interface with other programs.

Along the Internship Matlab has been used to Exploit the MLE+ environment [1], which is an open-source Matlab/Simulink toolbox for co-simulation with the whole-building energy simulator EnergyPlus.

Overall, the algorithms created in Matlab can be used for two different purposes:

1. To define the values of the controlled variables at each time step of the Energy plus simulation;
2. To produce multiple idf files in which the variables of the original idf, are changed according to the customised algorithm.

The second feature has been used in order to produce other archetypes, starting from the average archetype previously defined.

3.2 Modelling of the Existent Building stock

3.2.1 Data collection

Barcelona is selected as a case study to testate and demonstrate the proposed model for three main reasons:

(i) Barcelona's Commitment to Climate's roadmap [25] proposes that the city should have its per capita CO_2-emission levels cut down by the equivalent of 40% by 2030, respect 2005;

(ii) According to [25], the building sector represents roughly half of both the total municipal energy demand and CO_2 emissions;

(iii) No detailed data about the thermophysical properties of the building built along the past century is available;

Moreover, the reduction of the energy consumption of the building sector supports not only the COP21 targets but also the sustainability goal of the 2030 Agenda by the moment that 8.8% of the people in Barcelona could not maintain an adequate internal winter setpoint temperature [26].

First step: Category definition

As explained in the section about data collection (0), the buildings constructed in the same period represent a category as they share the same thermophysical properties. With regards to Barcelona, the number of buildings built along the last century is defined by [27] and Figure 13 reports the results through a bar chart.

Successively, according to the methodology, properties of the buildings built between 1940 and 1980 are indagated to understand in how many categories the period should be divided.

According to "TABULA web tool" [28], the buildings can be separated into two categories: 37'-59' and 60'-79'. Between those two categories, the second category has been chosen because it represents 30% of the total amount of buildings constructed in the last century, while the 37'-59' category represents the 21%.

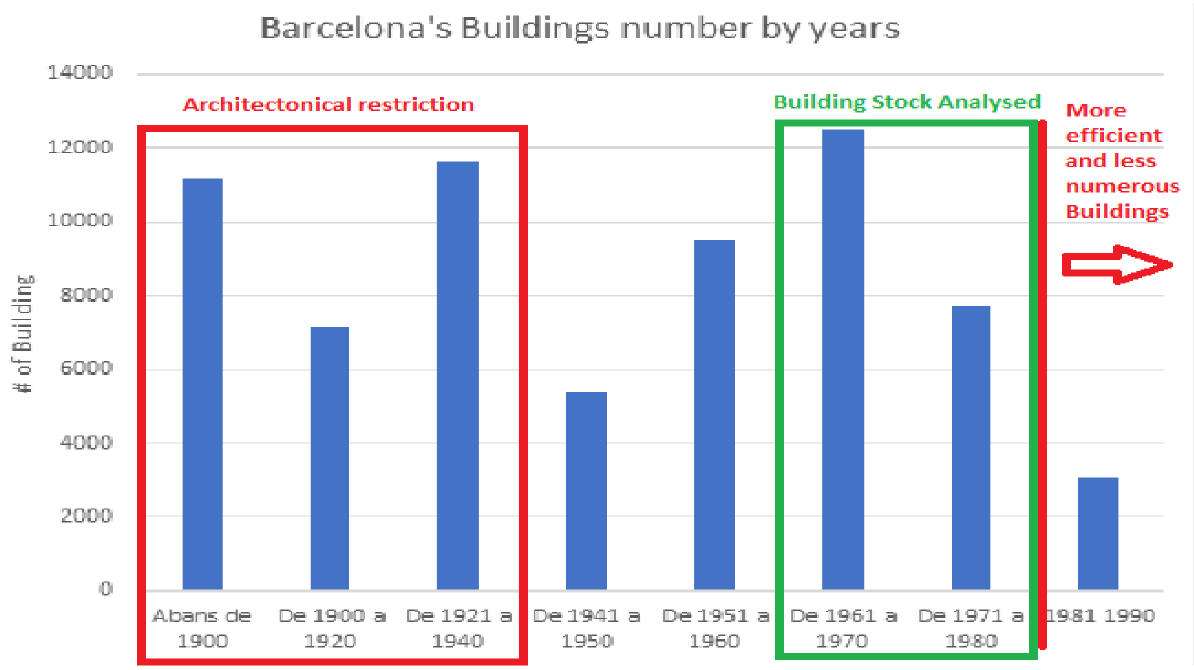


Figure 13: Number of Residential Buildings Built in Barcelona divided by decades. In red, the edifices neglected; in green, the category that is chosen as buildings stock for the case study.

Second step: Variable definition

Following the methodology, the next step of the data collection is the definition of the variable, which consists of:

- Defining the variables required to model the archetype throughout the categories of Form, Envelope, System and Operation.
- Defining the Variation's ranges of the variables.
- Assessing which are the discrete values that the variable can assume within these ranges.

The variables used to describe a generic archetype are reported in Table 3, whereas the variation's ranges and the discrete values are defined directly for the SVs defined by the studies [11] and [29] which have implemented a sensitivity analysis on similar Building categories and stratigraphy. Specifically, the range and the discrete values selected for the SVs are collected in Table 4.

Table 3 Variable used to describe a generic archetype

Geometry	Ground floor [m2]
	Ground floor [m2]
	External walls [m2]
	Roof [m2]
	Intermediate floor [m2]
	Windows [m2]
	Total floor area [m2]
	Number of floors
	Window to wall Ratio
	Side length (square hypothesis) [m]
	Floor's height [m]
	Total volume [m3]
Operation	Hourly exchange due to use [1/h]
	Hourly exchange by infiltration [1/h]
	Primary air flow [m3/h]
	Heating setpoint [C]
	Cooling Setpoint[C]
	People density [people/m^2]
	Light load [W/m^2]
Envelope	Thickness (t) [m]
	Conductivity(K) [W/m K]
	Density(d) [kg/m^3]
	Thermal Capacity (c) [J/kg K]
	Thermal resistance (R) [m^2 K/W]
	Solar Absorptance (a)
System	Global Efficiency Heating System
	Global Efficiency Cooling System
	Dual setpoint control

Table 4: Definition of the technologically acceptable values of the Significant variables

Category of the parameter	Significant variable		Range	Discrete variation Steps
Envelope	Absorptance	Roof	[0.1,0.9]	0.1
		Walls	[0.1,0.9]	0.1
	Thickness	Internal brick	[0.04,0.12]m	0.01 m
		External Brik	[0.08,0.16]m	0.01 m
		Roof block	[0.12,0.32]m	0.02m
		Clay	[0.03,0.09]m	0.01m
	Types of glass	Single	[5,6.4]	0.2 [W/m²k]
		Double	[2.3,3.7]	0.2 [W/m²k]
Operation	Heating set-point		[18,22] °C	0.2°C
	Cooling set-point		[24,28] °C	0.2°C
System	Heating Efficiency		[0.7,0.8]	0.01
	Cooling Efficiency		[2,3]	0.1
Form	Number of floors		[1,10]	1 floor

Third step: Average Archetype definition

The final step required to conclude the Data collection is the Average Archetype Definition. The average Archetype is defined by associating an average value to each Form, Envelope, System and Operation's variable previously defined.

For the definition of the *average Form variables' values*, TABULA's geometrical data have been used and Table 5 collects the result.

Table 5: Definition of the Average Archetype. Form Data.

	Variable	Value
Form data	Ground floor [m²]	161.70
	External walls [m²]	803.70
	Roof [m²]	161.70
	Intermediate floor [m²]	161.70
	Windows [m²]	103.00
	Total floor area [m²]	1153
	Number of floors	7
	Window to wall Ratio	0.128
	Side length (square hypothesis) [m]	12.7
	Floor's height [m]	2.5
	Total volume [m³]	2882

The *average Envelope variables' values* definition follows a Top-Down Procedure:

(i) Qualitative Stratigraphies and Transmittances of the structure are collected from TABULA. Figure 14 exposes the results.

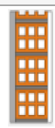
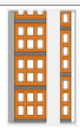
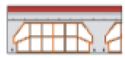
Roof 1	surface area	161.7m^2	Wall 2	surface area	282.9m^2
	type of construction / refurbishment measure	flat roof: one-way framework with prestressed joint cubierta plana, forjado unidireccional viguetas pretensadas		type of construction / refurbishment measure	masonry of coating bricks Muro de ladrillo de una hoja revestido
	picture			picture	
	U-value	1.92 W/(m^{2}K)		U-value	2.08 W/(m^{2}K)
Wall 1	surface area	520.8m^2	Floor 1	surface area	161.7m^2
	type of construction / refurbishment measure	cavity wall: brick,air cavity muro capuchino, ladrillo y cámara de aire		type of construction / refurbishment measure	one-way framework with prestressed joint forjado unidireccional de viguetas pretensadas
	picture			picture	
	U-value	1.33 W/(m^{2}K)		U-value	1.13 W/(m^{2}K)

Figure 14: Definition of the Average Archetype. Envelope Data. Qualitative Stratigraphy [28]

(ii) The complete Envelope's stratigraphy and average variables' values are then defined by adapting the material properties proposed by [11] for Mediterranean Buildings with the transmittance and the qualitative Stratigraphy proposed by TABULA through an iterative procedure. Table 6 reports the results in detail.

Table 6: Definition of the Average Archetype. Envelope Data. Detailed Stratigraphy.

Layer	Material	t [m]	k [W/m K]	d [kg/m³]	c [J/kg K]	a	R [m² K/W]	U [W/m² K]
Ground floor	Cobblestone	0.18	0.7	1500	880	-	0.26	1.13
	Floor block	0.18	0.66	1800	840	-	0.27	
	Clay	0.06	0.455	450	1200	-	0.13	
	Screed	0.03	0.9	1800	840	-	0.03	
	Tiles	0.02	1	2300	1300	-	0.02	
	Downward internal flux	-	-	-	-	-	0.17	
External walls	Horizontal external flux						0.04	1.59
	Plaster	0.02	1.4	1800	840	0.5	0.01	
	External brick	0.12	0.72	1800	840	-	0.17	
	Air gap	0.2	–	1.03	1010	-	0.17	
	Internal brick	0.08	0.9	2000	840	-	0.09	
	Plaster	0.02	1.4	1800	840	-	0.01	
	Horizontal internal flux					-	0.13	
Roof	Upward internal flux						0.04	1.93
	Cement	0.03	1.4	1000	840	0.5	0.02	
	Roof Screed	0.03	0.9	400	1000	-	0.03	
	Roof block	0.22	0.71	1800	840	-	0.31	
	Plaster	0.02	1.4	1800	840	-	0.01	
	Downward internal flux					-	0.10	
Intermediate floor	Upward internal flux						0.10	1.13
	Tiles	0.02	1	2300	1300	-	0.02	
	Screed	0.03	0.9	1800	840	-	0.03	
	Intermediate Floor block	0.18	0.29	1800	840	-	0.62	
	Plaster	0.02	1.4	1800	840	-	0.01	
	Downward internal flux					-	0.10	

Average Operation variables' values are selected equal to the one exploited by TABULA's calculation. Table 7 collects the parameters considered.

Table 7: Definition of the Average Archetype.Operation Parameters.

Operation parameters	**Ventilation**	
	Hourly exchange due to use [1/h]	0.4
	Hourly exchange by infiltration [1/h]	0.4
	Temperature set-point	
	Winter [c]	20.0
	Summer[c]	26.0
	Internal load	
	Constant internal load (people and lighting) [w/m^2]	3

Finally, regarding the *Average Operation variables' values*, TABULA suggests a Gas central heating system poor efficiency, therefore, according to [30] an AFUE, value of 0.75 is selected referring to the year 2000.

For the cooling system, referring to the year 2000, a SEER of 10.32 (COP of 2.77) has been selected according to[30].

It must be pointed out that the values refer to the annual efficiency, not to the nominal efficiency.

System typology	**Heating**
	Gas heating system, annual global efficiency of 0.75
	Cooling
	Electric cooling system, annual COP of 2.77

3.2.2 Archetypes Definition

Archetypes are created by variating the values of the SVs, while the other variables are maintained constant and equal to the average values defined for the average archetype. The selection of one specific discrete value for each significant variable is based on probabilistic consideration, which requires the definition of the statistical distribution associated with the SVs, as explained in section 2.1.3. Throughout the case study, when real data are not available, normal and bimodal distributions are assumed, and the mean value is set equal to the one defined in the Average Archetype, as suggested by [11]. Specifically, the distributions are built in a way to include 95% of the population within the ranges specified. Therefore, the sigma of the normal distribution is set as:

$$\sigma = \frac{\text{range}_{\text{limit}} - \mu}{2}$$

Figure 15 gives a graphical explanation of the formula abovementioned and Table 8 collects the overall results.

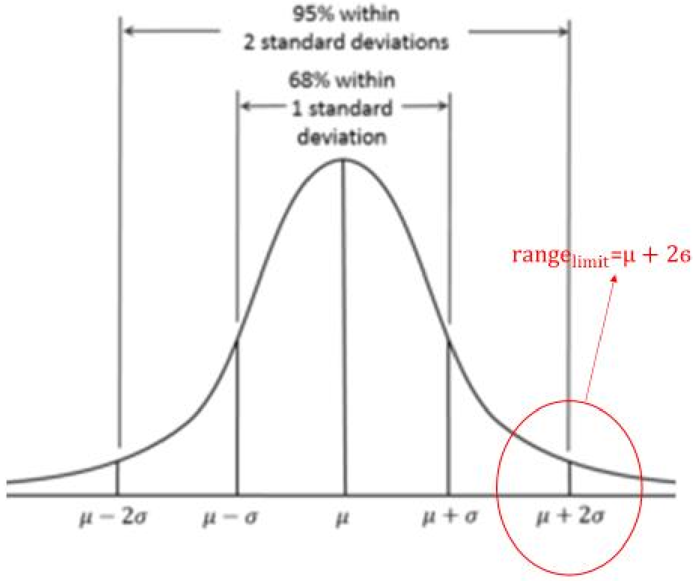


Figure 15 : Evaluation of the sigma value.

Table 8 Statistical Distribution of the Signifactive Variables

Variable parameter					
Category of the parameter	**Types of parameters**		**Distribution**	**Mean value (μ)**	**Standard deviation (σ)**
Envelope	Absorptance	Roof	Normal	0.5	$\frac{righ_{limit} - \mu}{2}$
		Walls	Normal	0.5	$\frac{righ_{limit} - \mu}{2}$
	Thickness	Internal brick	Normal	0.08	$\frac{righ_{limit} - \mu}{2}$
		External brick	Normal	0.7	$\frac{righ_{limit} - \mu}{2}$
		Roof block	Normal	0.22	$\frac{righ_{limit} - \mu}{2}$
		Clay	Normal	0.06	$\frac{righ_{limit} - \mu}{2}$
	Types of glass	Single	Bimodal	5.7	$\frac{righ_{limit} - \mu}{2}$
		Double		3	$\frac{righ_{limit} - \mu}{2}$
Operation	Heating set-point		Normal	20	$\frac{righ_{limit} - \mu}{2}$
	Cooling set-point		Normal	26	$\frac{righ_{limit} - \mu}{2}$
System	Heating global efficiency		Normal	0.8	$\frac{righ_{limit} - \mu}{2}$
	Cooling global efficiency		Normal	2.5	$\frac{righ_{limit} - \mu}{2}$
Form	Number of floors		Real data distribution		

3.3 Retrofit of the Building Stock

As the validation of the methodology is independent of the approach, a parametrization analysis is chosen. Technological improving regarding Envelope and System are proposed to reduce the energy demand and the environmental impact of the overall stock. In Table 9 a summary of the measure considered is reported.

Table 9: Summary of the measure analysed with the parametric approach.

Technology	Measure proposed
Window	Replacing the single plan glass in the archetypes that still have it and starting from the archetype with high final energy consumption.
System	Replacing the Cooling and Heating system starting from the archetype with high final energy consumption
Insulation	Adding an insulation layer to the building starting from the archetype with high final energy demand.

Regarding the Evaluation of the NPV, the maintenance and the residual cost of the technology are not considered, whereas the other parameters are set according to Table 10.

Table 10 Factors used for the NPV Evaluation

Factors	Value
Inflation Rate of Energy [31]	5.5%
Annual discount rate[31]	3.5%
Cost of CO_2 [32]	25 €/ton

Finally, in Table 11, the conversion factor used to produce the technological and economic results are presented.

Table 11 Economic and Technological conversion factors related to the production system

Energy Vector	$kWh_{primary}/KWh_{final}$ [33]	$gCO2/kWh_{final}$ [33]	Cost (€/kWh)
Gas	1.07	201	0.067 [34]
electricity	2.21	444	0.238 [35]

3.3.1 Windows

Regarding the windows, economic and technological information is set according to [16] and shown in Table 10. Specifically, each window is characterized by the cost in terms of [€/m2] the transmittance U and the solar factor (g), which is defined as the percentage of thermal energy that passes through it, compared to the total energy incident on the surface itself.

Table 12: Economic and Technological assumption for the transparent component.

Window type	Description	U_W [W/(m² K)]	g-value	Cost [€/m²]
Solution 1	4/16/4 Double glazing, w/o Argon	2.83	0.755	166.60
Solution 2	4/15/4 Double glazing, low-E, with Argon	1.1	0.609	179.85
Solution 3	6/16/6 Double glazing, low-E and solar control, with Argon	1.29	0.333	220.81
Solution 4	6/12/4/12/4 Triple glazing, low-E and solar control, with Argon	0.7	0.294	266.41
Solution 5	4/16/4/16/4 Triple glazing, low-E, with Argon	0.7	0.501	217.19

3.3.2 Insulation

The insulation measures consider two types of materials: glass wool, applied to the interior and exterior side of the perimetral wall, and extruded polystyrene (XPS) on the roof. Table 13 shows the technological and economic details related to the measures [36].

Table 13: Economic and Technological assumption related to the insulation measure.

Surface		Type	Technology	U-value ($W/m^2/K$)	Variable cost (€/m^2)
Wall	Interior	Standard	Glass wool 15 cm	0.30	65
		Deep	Glass wool 25 cm	0.20	100
	Exterior	Standard	Glass wool 10 cm	0.40	120
		Deep	Glass wool 20 cm	0.20	210
Roof		Standard	XPS 15 cm	0.21	80
		Deep	XPS 30 cm	0.13	95

With the aim of analysing intermediate values beyond the ones reported, the value of Table 13 is linearly interpolated, and the final summary of the insulation measure is reported in Table 14.

Table 14: Economic and Technological assumption related to the insulation measure obtained by linear interpolation of the value reported in Table 13.

Surface	Type	Technology	Thermal Conductivity (W/mK)	Variable cost (€/m^2cm)	Range (cm)
Wall	Interior	Glass wool	0.045	3.5	[15;25]
	Exterior	Glass wool	0.04	9	[10;20]
Roof	Terrace	XPS	0.032	1	[15;30]

3.3.3 System

Regarding the heating system, Economic and technological information was found in the literature [36] and values are reported in Table 15.

Table 15: Economic and Technological information related to the heating production system

Type	Fuel	Technology	η (%)	Variable cost (€/kW)	Fixed cost (€/u)	Instal. cost (€/u)
Boiler	gas	condensing	0.91	19	2000	1000
Heat pump	electricity	air-to-air	4.57	415	0	800

Regarding the air conditioning system, results were not found from the literature review. For this reason, the cost for unit is set according to [37], the installation cost equal to 800EURO/unit according to [36] and the Annual SEER equal to 17 according to [38]. Results are presented in Table 16.

Table 16 Economic and Technological information related to the cooling production system

Type	Fuel	*Annual COP*	cost (€/kW)	Instal. cost (€/u)
Air to air, air conditioning	electricity	3.89	$-79.167[kW]^2 + 850[kW] - 880.21$	800

3.4 Results

3.4.1 Surrogate model's size definition

As explained in the model size definition (2.1.4), the minimum size of the surrogate model is obtained when the error, which evaluates the quality of the histogram' shape, goes above the threshold. Regarding the case study, first, two histograms are built sorting the Energy Demand for Heating and Cooling separately. The evolution of these distributions' shapes is reported in Figure *16* and Figure 17.

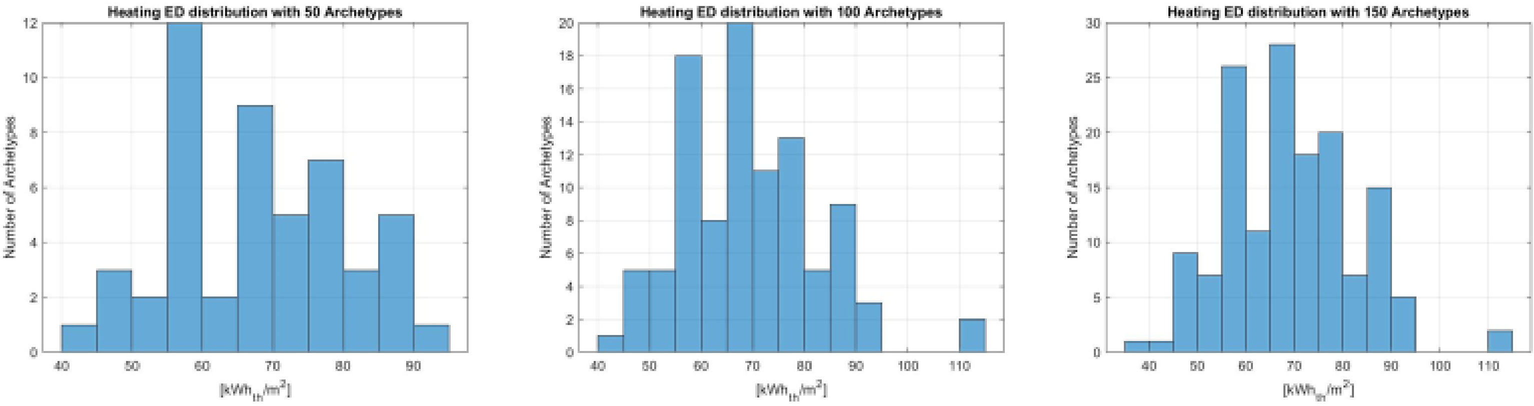
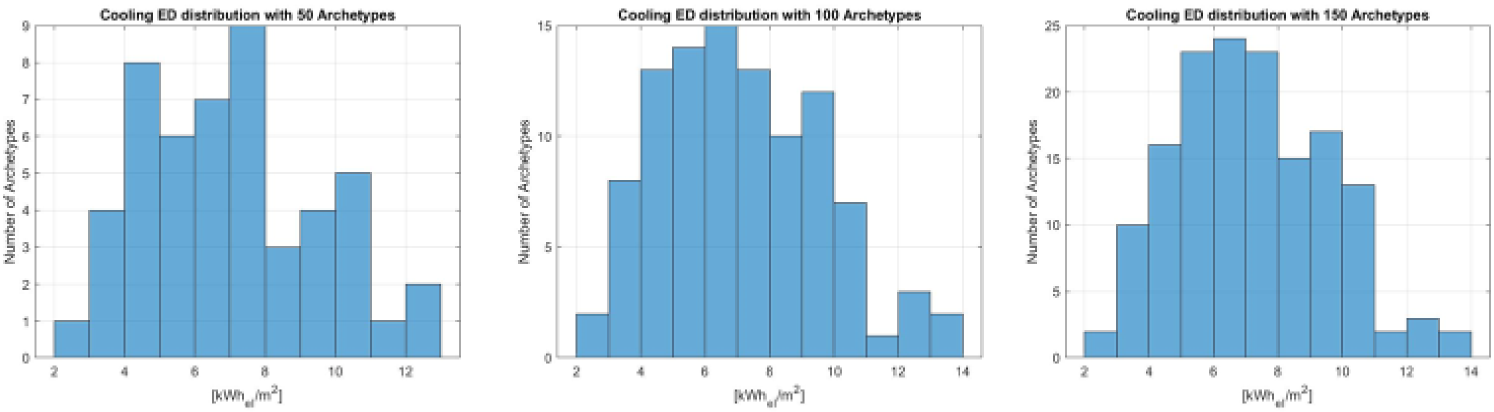


Figure 16 *Evolution of the final heating demand distribution: the shape on the left is obtained with 50 Archetypes, the shape in the centre is obtained with 100 Archetypes, the shape on the right is obtained with 150 Archetypes.*



.Figure 17: Evolution of the final cooling demand distribution: the shape on the left is obtained with 50 Archetypes, the shape in the centre is obtained with 100 Archetypes, the shape on the right is obtained with 150 Archetypes.

While the distributions evolve, the error related to the histograms' shape is evaluated each time that a new archetype is added into the model. When both the errors result below the threshold, the minimum size is reached. In details, the threshold is settled at 3% and the NSM results equal to 169 archetypes. Figure 18 and Figure 19 report graphically the evolution of the error related to the heating and cooling distribution, respectively.

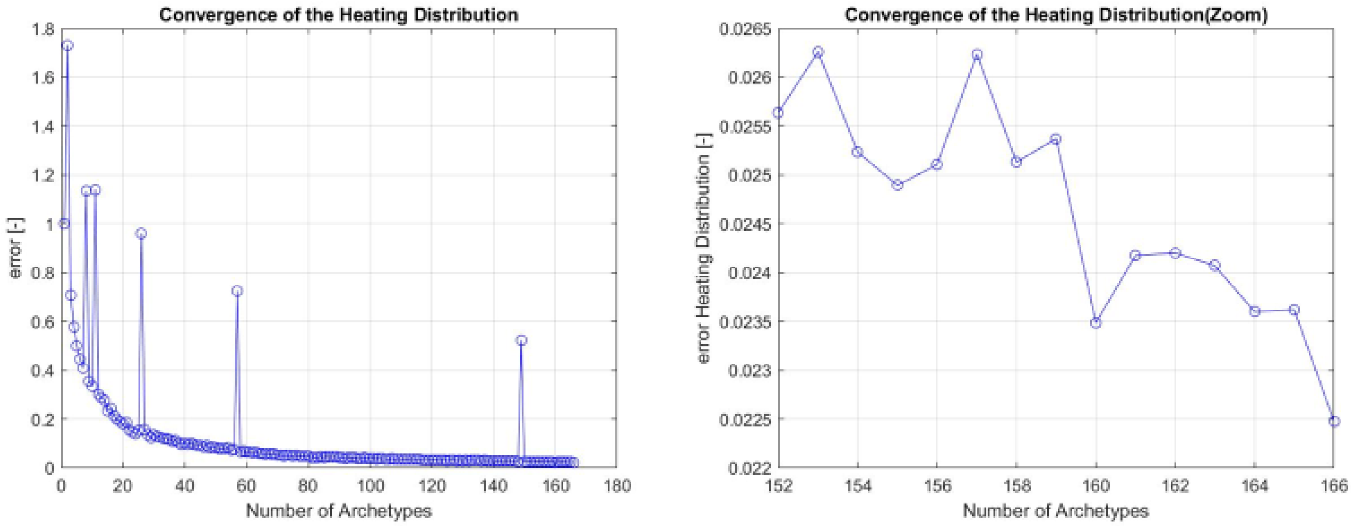


Figure 18: On the left, the convergence of the heating energy demand distribution on the left; On the right, a Zooming of the lasts iterations.

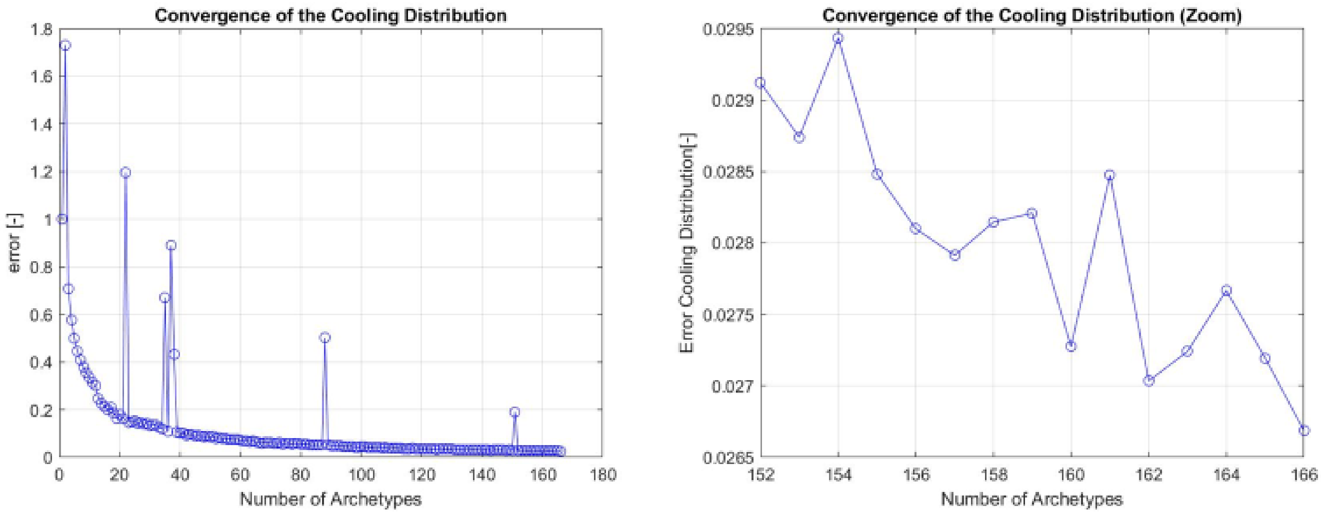


Figure 19: On the left, the convergence of the cooling energy demand distribution; On the right, a Zooming of the lasts iterations.

In order to understand the difference between the surrogate model and the complete model, the distribution of the significant variables across the stock can be seen in Figure 20, comparing the Surrogate and the Complete model. Comparison of all the other variables is reported in the section 6.1 of the Annex.

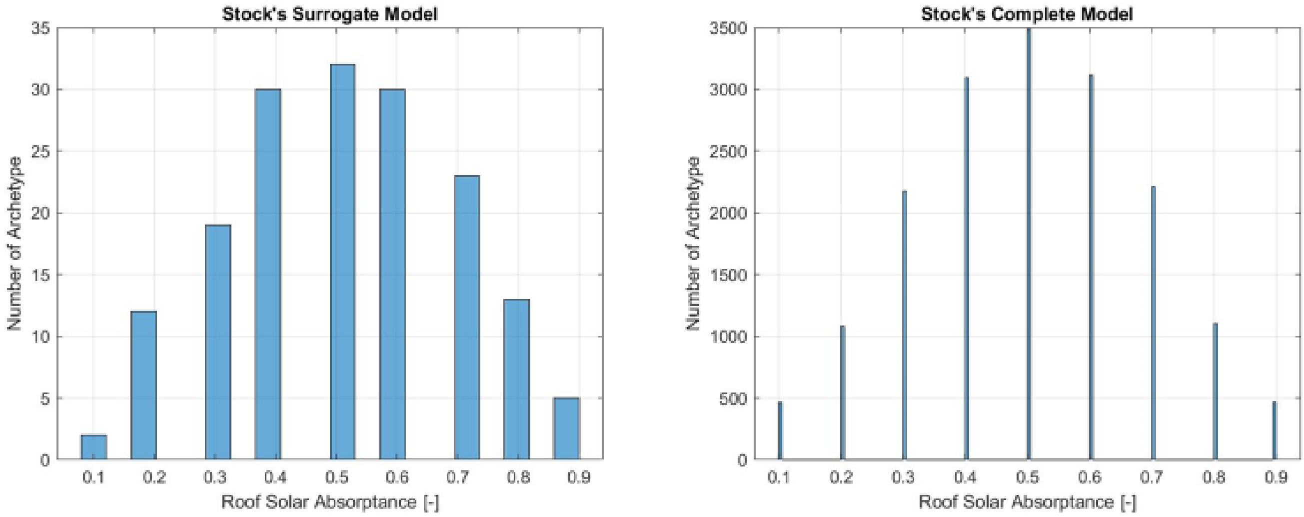


Figure 20: Distribution of the Roof Solar Absorptance. On the left, the variable distribution in case of the entire Building stock; on the right, the variable distribution across the surrogate model.

3.4.2 Existent Buildings Stock

The distributions of the final energy demand for heating and cooling and final size for heating and cooling are obtained as the output of the surrogate model. Figure 21 reports the distribution of the ideal energy and power demand for cooling, showing a mean value of 20 kWh_{TH}/m^2 and 3.5 kW_{TH}/floor, respectively.

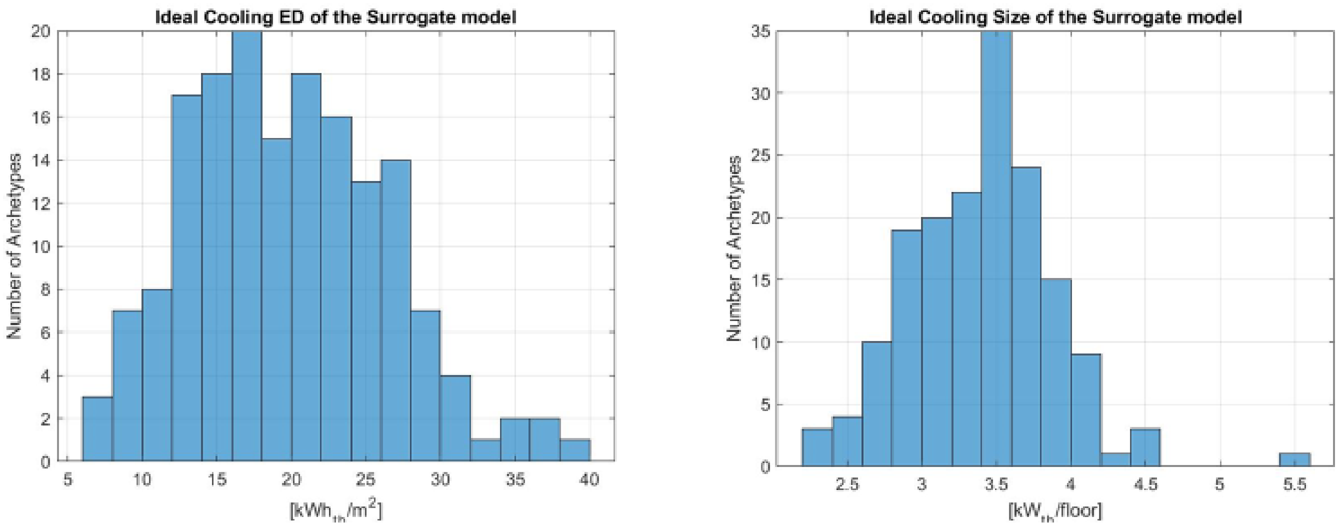


Figure 21 SURROGATE MODEL: On the left, the ideal cooling energy demand distribution; on the right, the ideal cooling size distribution.

On the other hand, Figure 22 reports the distribution of the ideal energy and power demand for heating, showing a mean value of 55 kWh_{TH}/m^2 and 7 kW_{TH}/floor, respectively.

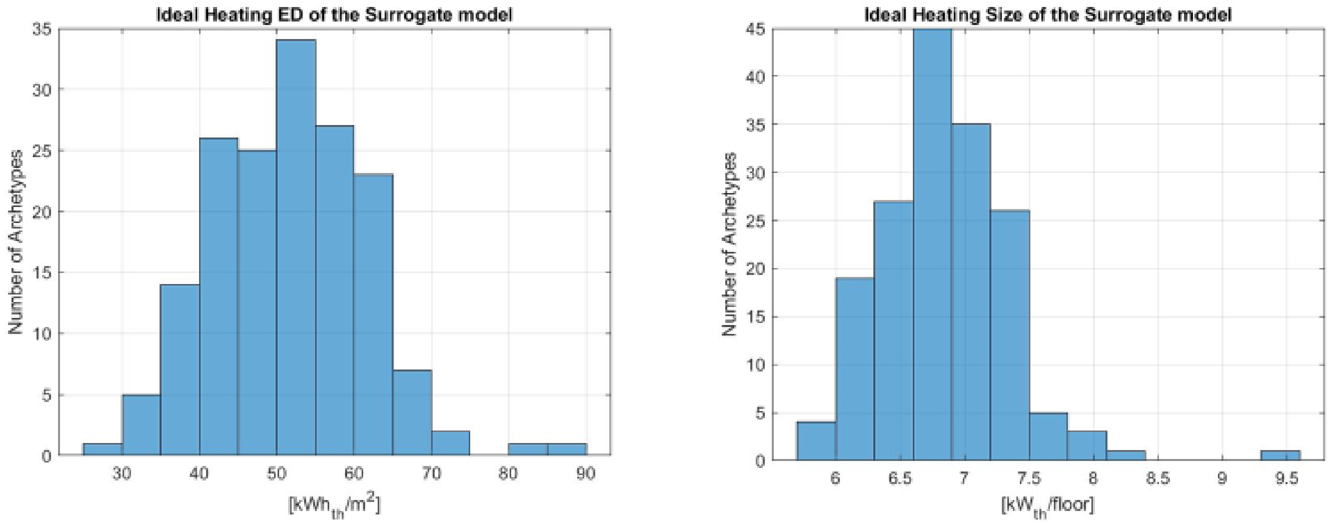


Figure 22 SURROGATE MODEL: On the left, the ideal heating energy demand distribution; on the right, the ideal healing size distribution.

Once evaluated the ideal profile, the information about the system is added and, therefore, the real power and energy demand of each building is forecasted. Figure 23 reports the distribution of the ideal energy and power demand for cooling, showing a mean value of 7 kWh_{TH}/m^2 and 1.3 kW_{TH}/floor, respectively.

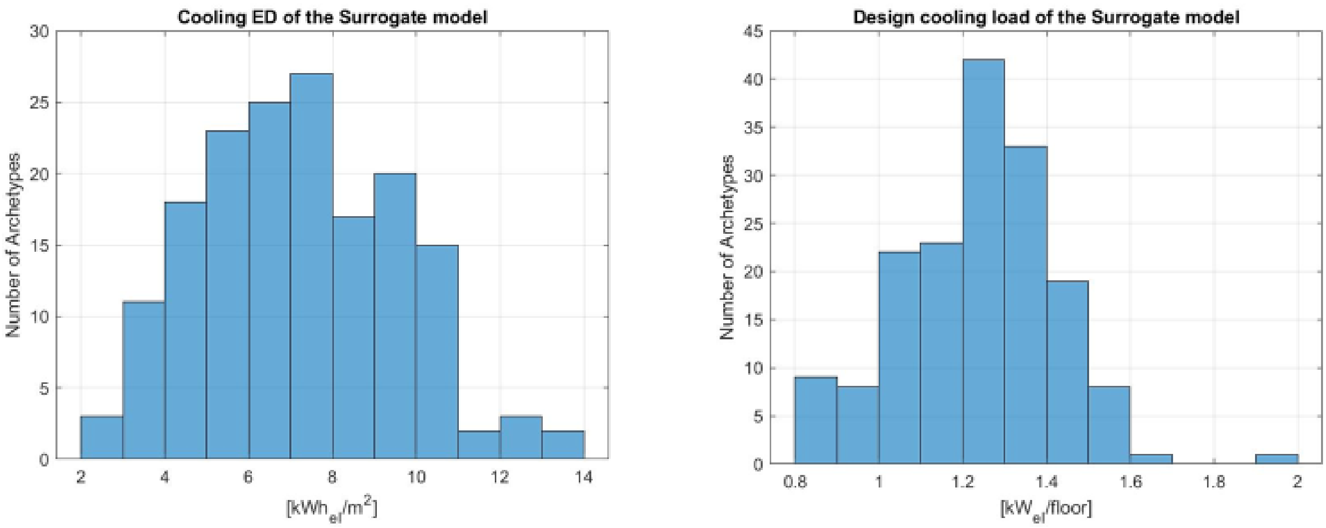


Figure 23 SURROGATE MODEL: On the left, the final cooling energy demand distribution; on the right, the final cooling size distribution.

On the other hand, Figure 24 reports the distribution of the ideal energy and power demand for heating, showing a mean value of 70 kWh_{TH}/m^2 and 9 KW_{TH}/floor, respectively.

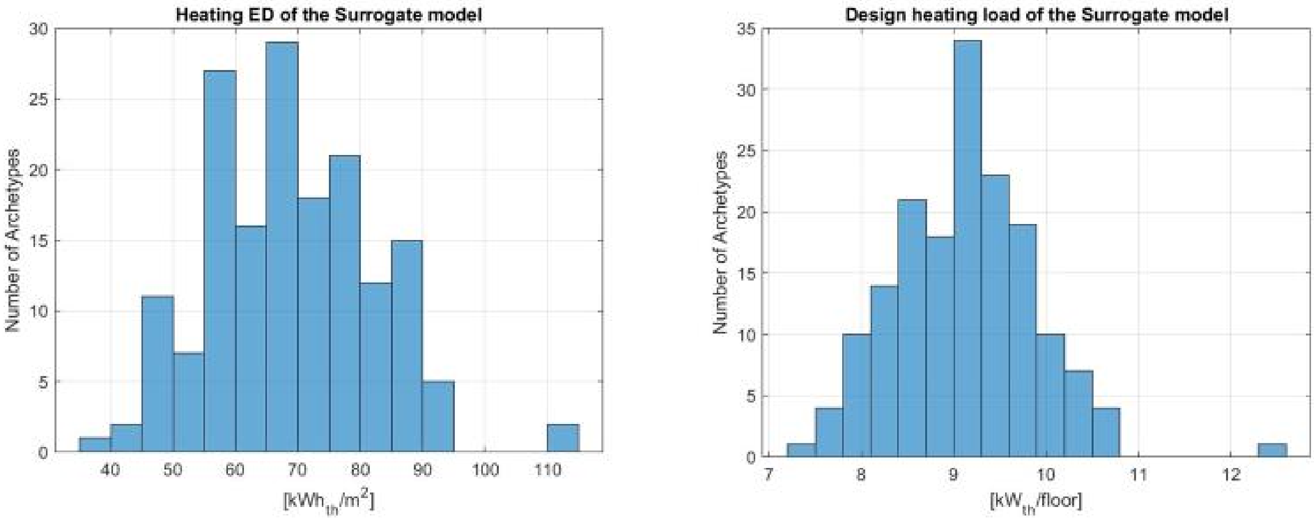


Figure 24 SURROGATE MODEL: On the left, the final heating energy demand distribution; on the right, the final heating size distribution.

With an error minor then 3%, it can be assumed that these distributions have the same shape of those that would be obtained with a model composed of NB archetype. Therefore, as explained in section 2.1.4, the output distributions of the model are multiplied for NB/NSM in order to obtain distribution that refers to the entire building stock. Results are shown in Figure 25 and Figure 26 and remark the general trend already seen in the figures Figure 23 and Figure 24, whereas the number of represented building increase.

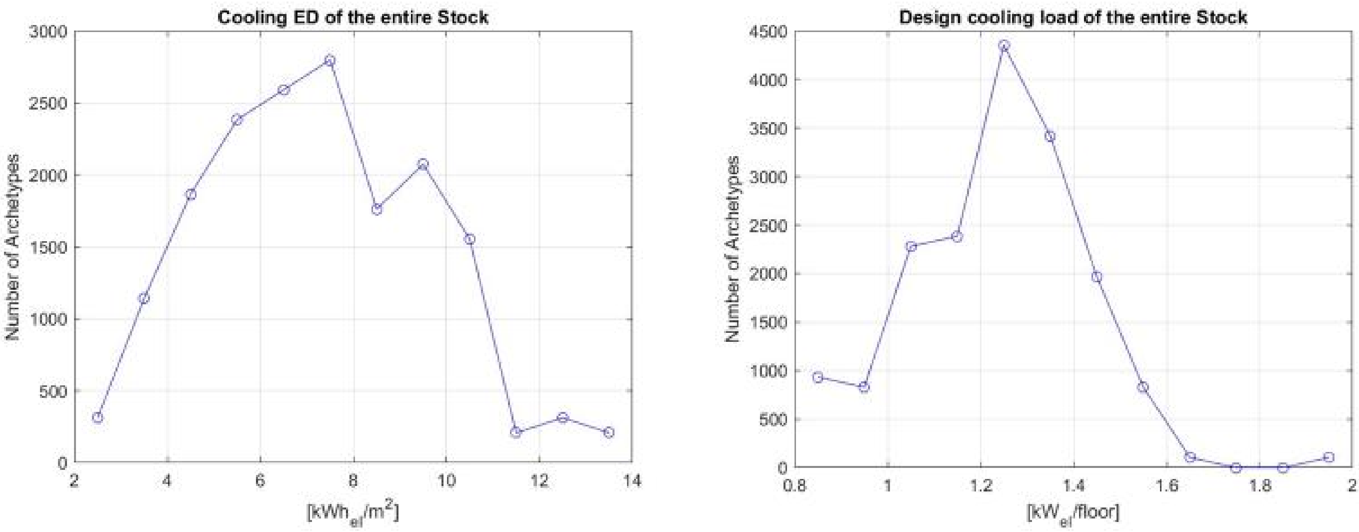


Figure 25 COMPLETE MODEL: On the left, the final cooling energy demand distribution; on the right, the final cooling size distribution.

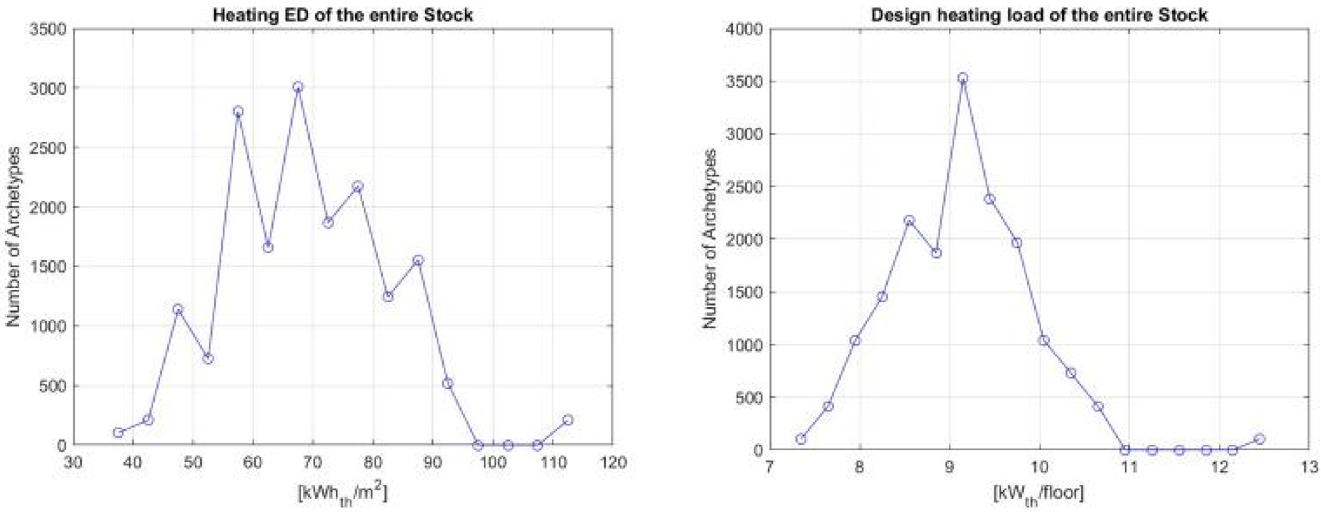


Figure 26 COMPLETE MODEL: On the left, the final cooling energy demand distribution; on the right, the final cooling size distribution.

In addition to the previous results, in order to completely describe the stock behaviour, information about the cost per square meter and the environmental impact of the energy demand are obtained throughout the conversion factor of Table 11. Results are reported in Figure 27 and Figure 28.

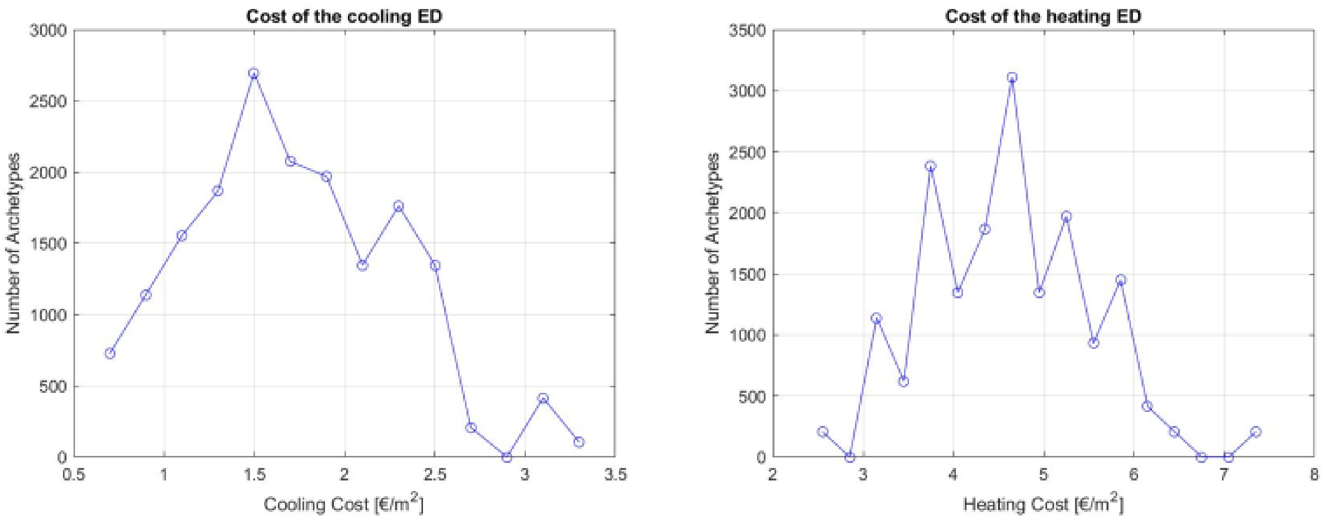


Figure 27 Cost in €/m^2 of the cooling and energy demand.

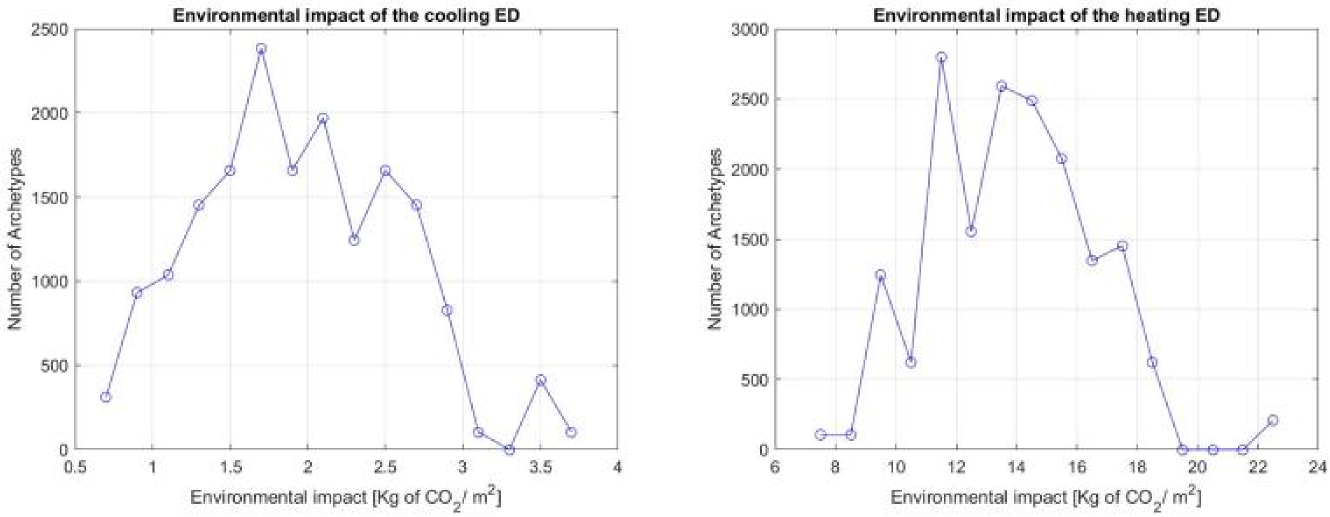


Figure 28 Environmental Impact in kg of CO_2/m^2 of the cooling and energy demand.

3.4.3 Retrofit

According to the section 2.2, different indicators are evaluated to quantify the economic and technological behaviour of the retrofit measure analysed. Specifically:

- PEC, CES and PPS are calculated to track the technological improvement obtained within cooling and heating demand;
- NPV, Incentives and PBT are evaluated to study the economic impact of the retrofit;

Those indicators are used to create images with a similar layout able to give information at different levels, as explained in 2.2.2. Overall, the same procedure will be applied for different categories of measure, exploring different configuration for each measure.

3.4.3.1 Windows

The window retrofit is applied in all the buildings of the stock characterized by single plane windows. The different windows' technologies analysed are those reported in Table 12.

Regarding the PES indicator, results shown in Figure 29 report the effect of the various technologies on the buildings in absolute and relative terms. The maximum PES is reached with the window characterized by the transmittance of 0.7 W/m^2K and the solar factor of 0.294. Indeed, by applied this window to all the stock a PES of 40GMh is reached accounting for roughly 28% of the total Cooling ED of the Stock. In contrast, the relative PES reached with the window characterized by the transmittance of 2.83 W/m^2K and the solar factor of 0.755 is about 7%.

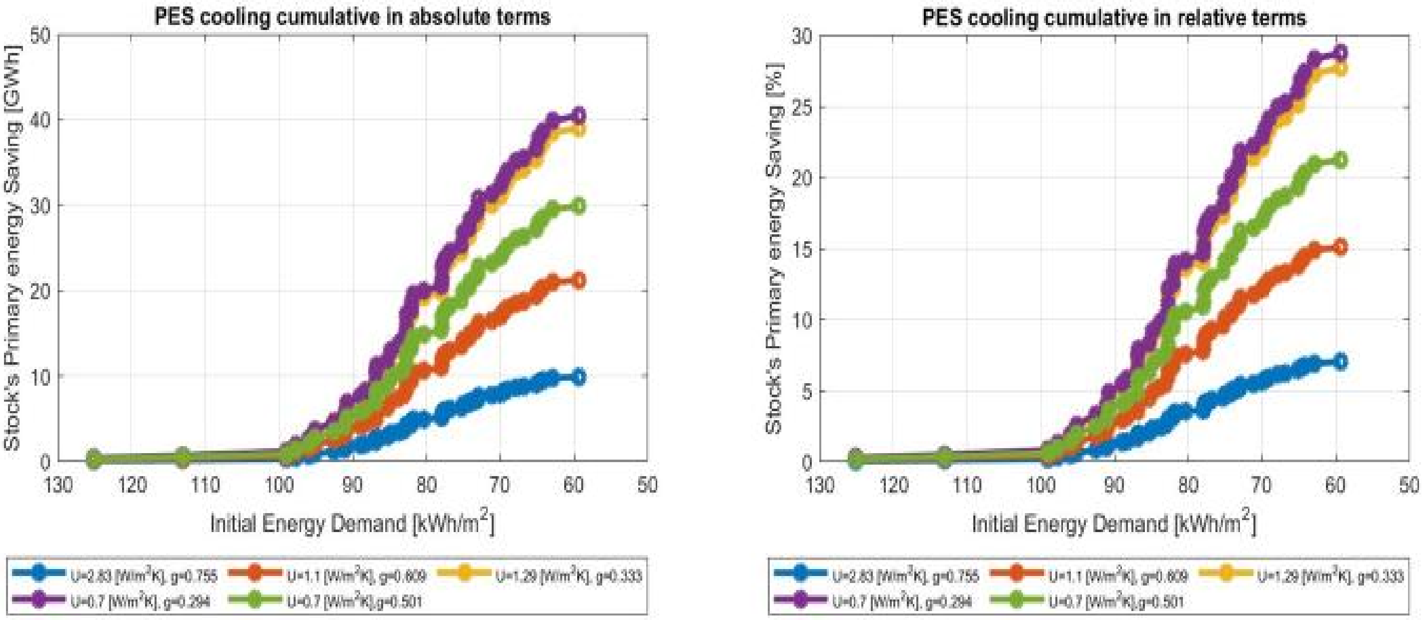


Figure 29 WINDOWS REPLACEMENT: PES INDICATOR, COOLING SHARE. On the right, the indicator in relative value; on the left the indicator in absolute value.

Focusing on the heating share, results are shown in Figure 30. The maximum PES is reached with the window characterized by a transmittance of 1.1W/m^{2}K and a solar factor of 0.609. Indeed, by applying this window to all the stock, a PES of 35GMh is reached accounting for roughly 2.7% of the total Heating ED of the Stock. On the other hand, the relative PES reached by the window, which is best performed in cooling demand, has a negative trend because, compared to the original window, the lower solar factor increases the heating energy demand and, therefore, produces a negative economic benefit across the buildings.

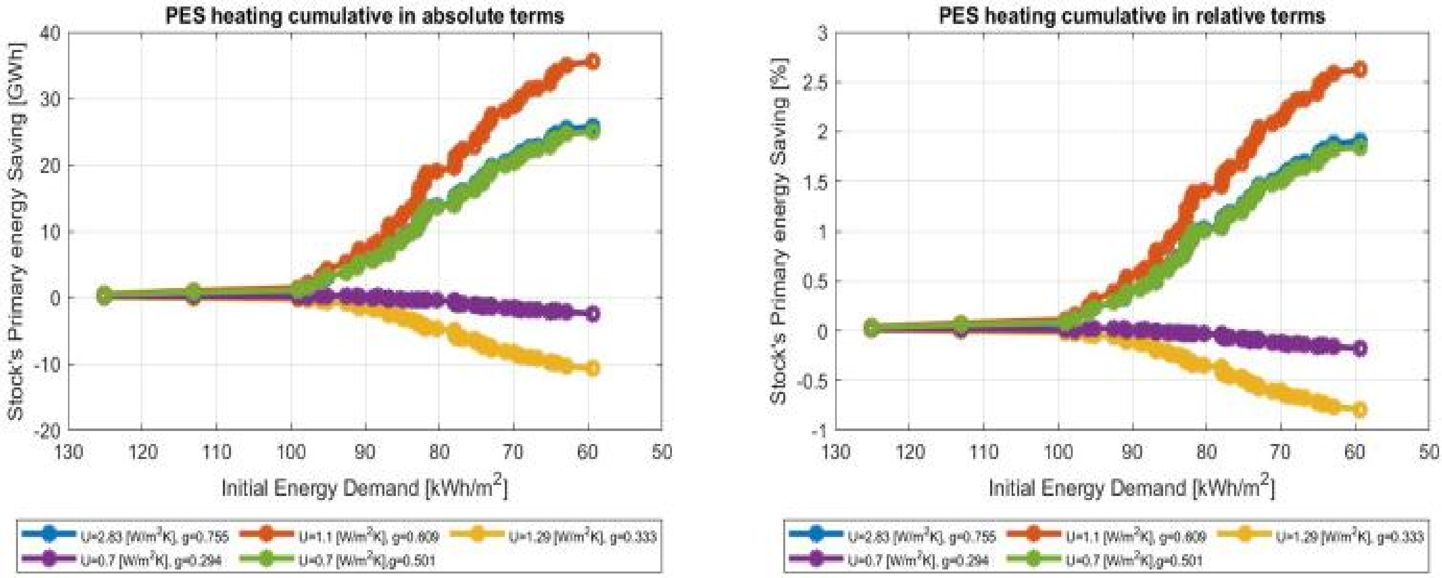


Figure 30 WINDOWS REPLACEMENT: PES INDICATOR, HEATING SHARE. On the right, the indicator in relative value; on the left, the indicator in absolute value.

Finally, the results about the total share showed in Figure 31 define what the technology configuration that ensures the best performance along all the year is. The results illustrate that two windows reach almost the same performance for a total PES of 55GWh, equivalent to 3.7% of the total stock's ED. The first one is the window characterized by a transmittance of 1.1W/m^{2}K and a solar factor of 0.609, which ensures high energy saving during the heating period. The second is the window characterized by a transmittance of 0.7W/m^{2}K and a solar factor of 0.5, which ensures good performance in both the periods.

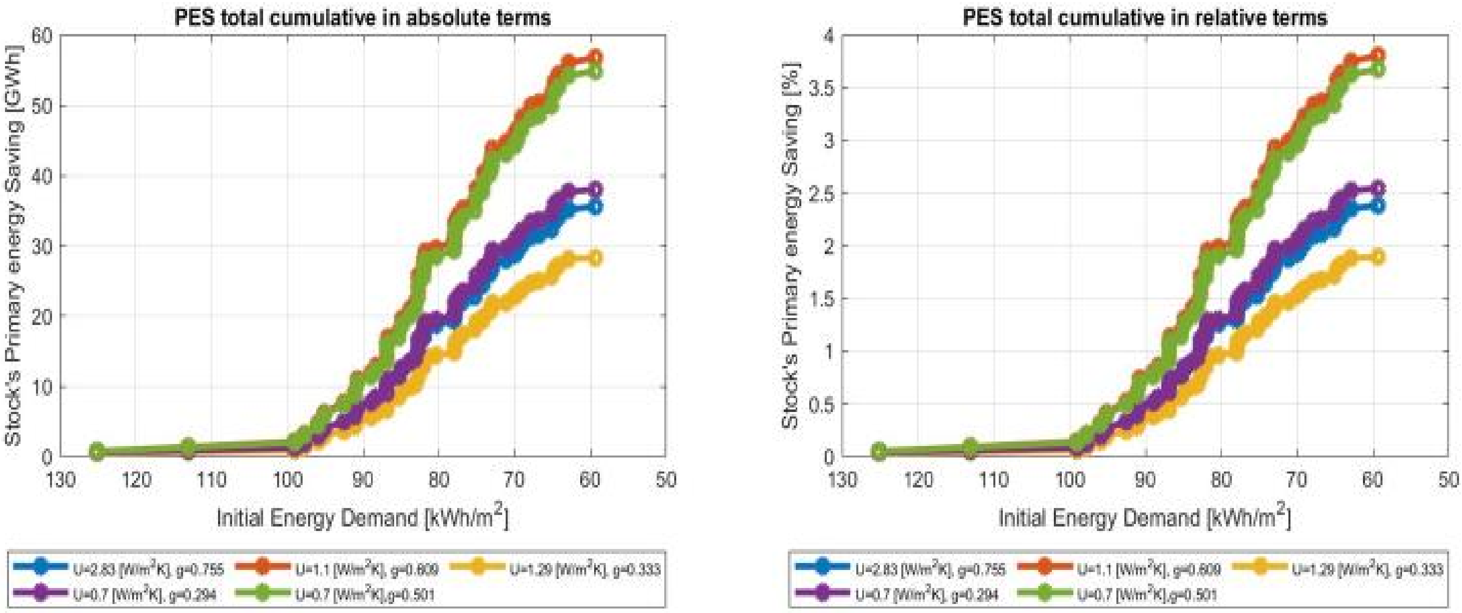


Figure 31 WINDOWS REPLACEMENT: PES INDICATOR, TOTAL SHARE. On the right, the indicator in relative value; on the left the indicator in absolute value.

After evaluating how the proposed solution performs in terms of energy saving, it is important to study the improvement in terms of Carbon Energy Saving. Indeed, through the graphs, the policymaker will be directly able to understand what should the portion of the building stock that has to be retrofitted to accomplish the future targets proposed by the Europeans directives. The results are reported in

Figure 32, Figure 33 and Figure 34 account respectively for the cooling, heating and total share. Regarding the total share, the shapes slightly differ from the ones in Figure 31 because the PES obtained during the cooling produce a greater CES due to the electricity saving. For this reason, the window characterized by a transmittance of 0.7W/m^{2}K and a solar factor of 0.5 is the best technology to produce the greatest energy saving, accounting for 9Mtons of CO_2 saved, equal to almost 3% of the total CO_2 produced.

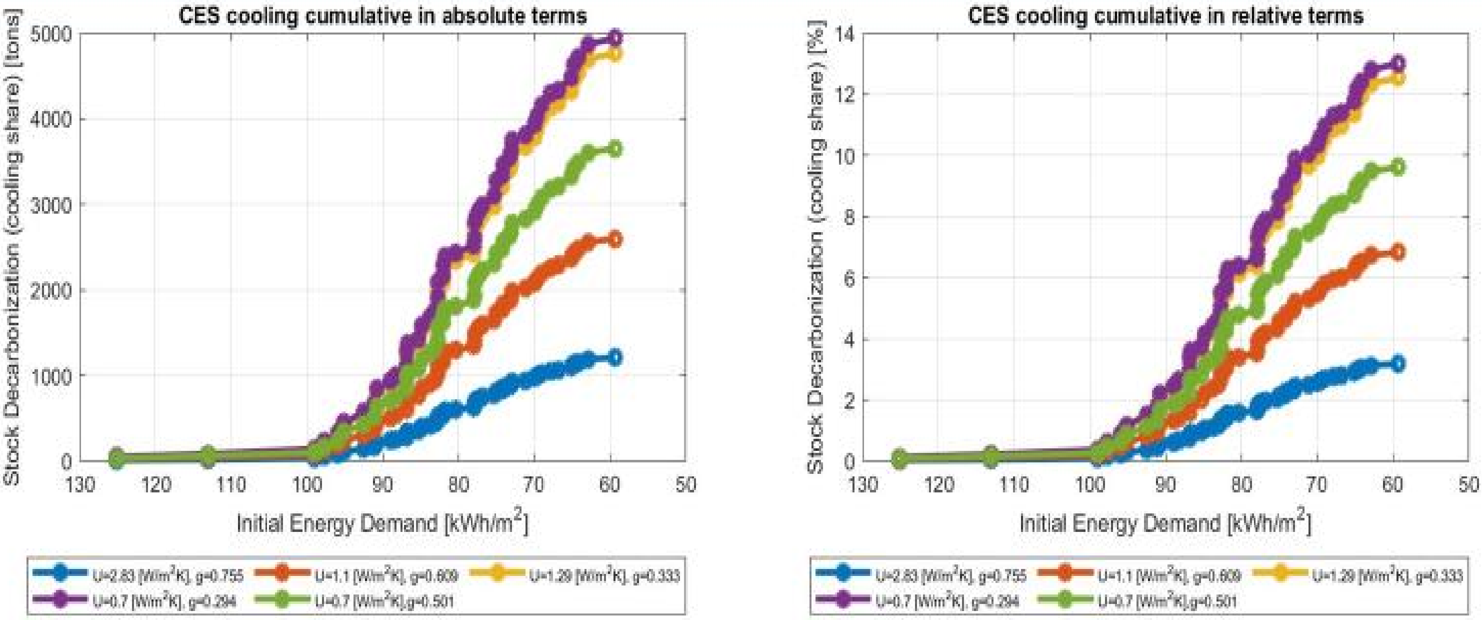


Figure 32 WINDOWS REPLACEMENT: CES INDICATOR, COOLING SHARE. On the right, the indicator in relative value; on the left the indicator in absolute value.

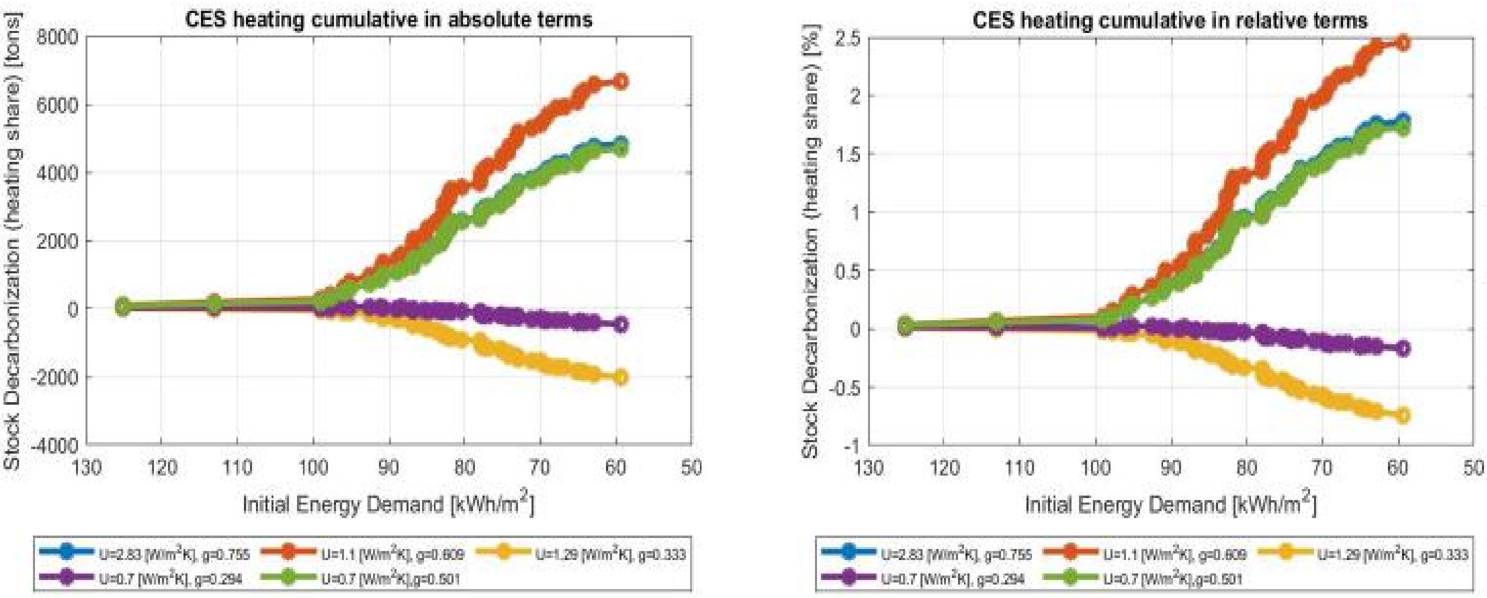


Figure 33 WINDOWS REPLACEMENT: CES INDICATOR, HEATING SHARE. On the right, the indicator in relative value; on the left the indicator in absolute value.

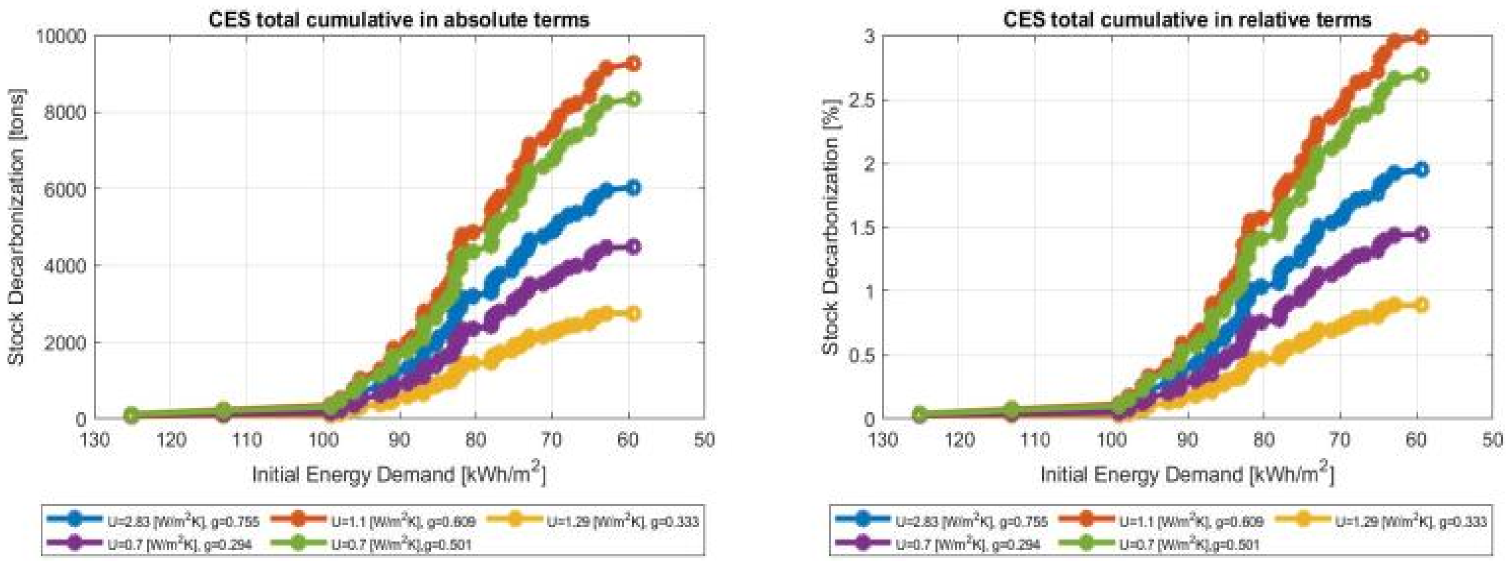


Figure 34 WINDOWS REPLACEMENT: CES INDICATOR, TOTAL SHARE. On the right, the indicator in relative value; on the left the indicator in absolute value.

The last indicator evaluated within the technical analysis framework is the Power Peak Saving in MW. Differently from PES and the CES, results of the PPS are divided only for the cooling and heating since the sum of the power demand exploits different energy vectors (natural gas and electricity) and happens in different periods of the year.

Regarding the Cooling share, results are shown in Figure 35. As happened for the PES and CES, the maximum PPS is reached with the window characterized by a transmittance of 0.7 W/m^2K and a solar factor of 0.294. The PPS is obtained to account for 13MW, which is equal to roughly 9% of the total Cooling Peak Power Demand of the Stock. In contrast, the relative PPS reached with the window is characterized by a transmittance of 2.83 W/m^2K and a solar factor of 0.755 is about 2.5%.

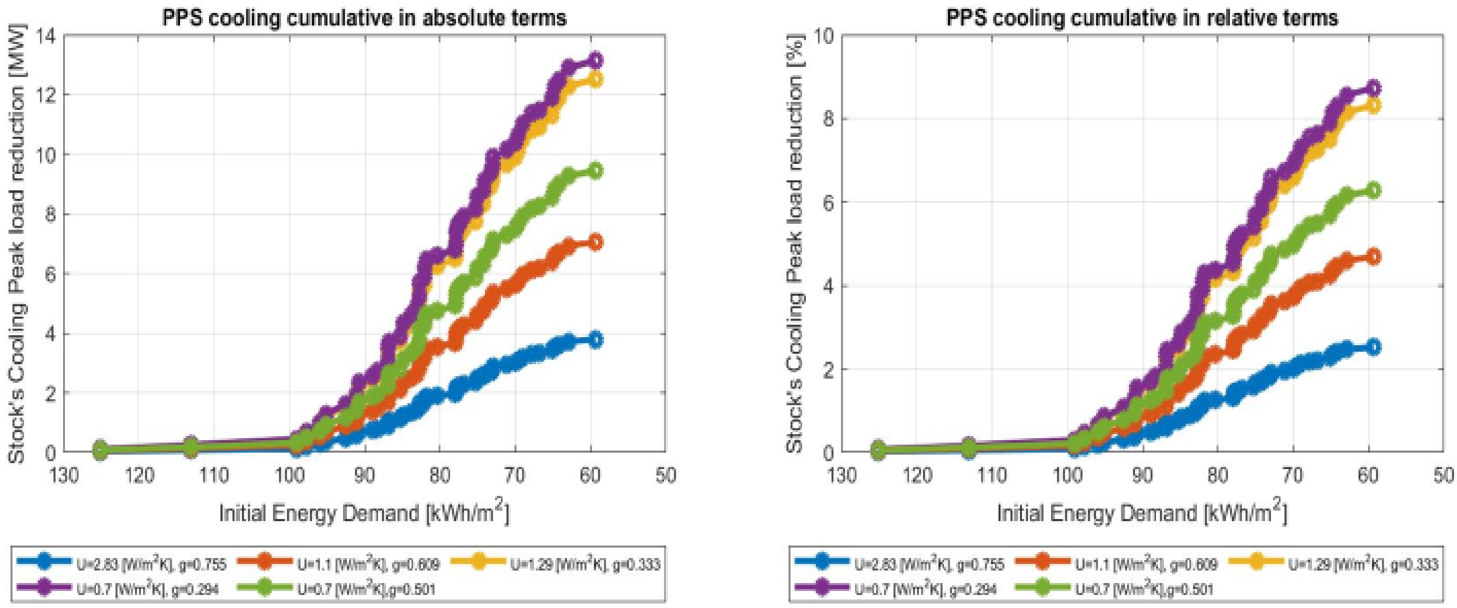


Figure 35 WINDOWS REPLACEMENT: PPS INDICATOR, COOLING SHARE. On the right, the indicator in relative value; on the left the indicator in absolute value.

Focusing on the heating share, results are shown in Figure 36. Oppositely with what happened for the PES and CES case, the maximum PPS is reached with the two windows characterized by a transmittance of 0.7W/m^2K. Indeed, as the solar gains are not considered during the sizing day, by applying these windows to all the stock a PPS of 45MW is reached, accounting for roughly 4% of the total heating Peak Power Demand of the Stock.

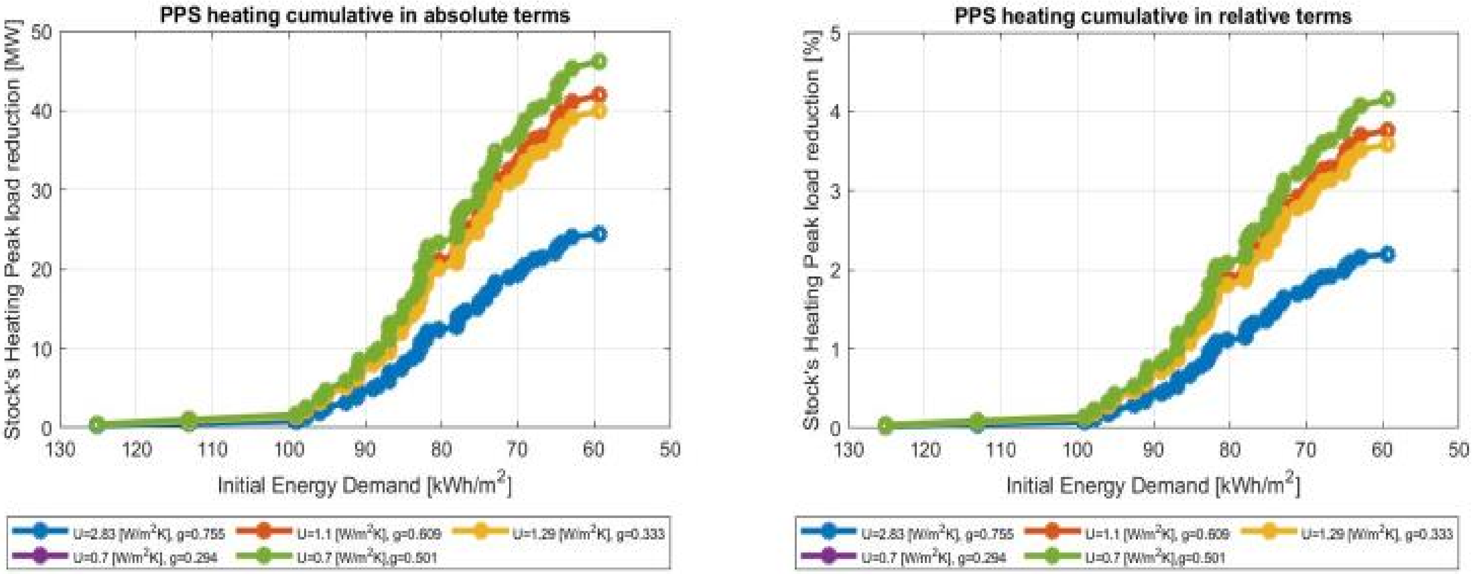


Figure 36 WINDOWS REPLACEMENT: PPS INDICATOR, HEATING SHARE. On the right, the indicator in relative value; on the left the indicator in absolute value.

After producing the Technological indicators, the Economic performances of the solution are evaluated through the economic indicators. Figure 37 illustrates the results regarding the NPV and PBT indicators. In details, only the two windows that performed as the best technology for the PES at the global level achieved a positive NPV considering a life span of 30 years. This behaviour is because of the low PES of the other three technologies that determines a low value of Economic savings which are the only possible profit for a retrofit measure. Among the two windows performed with a positive NPV, the one characterized by the transmittance of 1.1 W/m^2K and the solar factor of 0.609 produces an overall stock income of 55 Million of euro with an average PBT of 23 years. Finally, on the right of Figure 37 the value of the NPV and the PBT is reported when the measure is applied to all the stock. In that image it is clear that, among the five technologies analysed, the window characterized by the transmittance of $1.1W/m^2K$ and the solar factor of 0.609 achieves the best economic performances as it achieves the highest Net Present Value (around 60 million of €) and the lowest PBT (about 30 year of simple PBT and 23 year for the complete PBT).

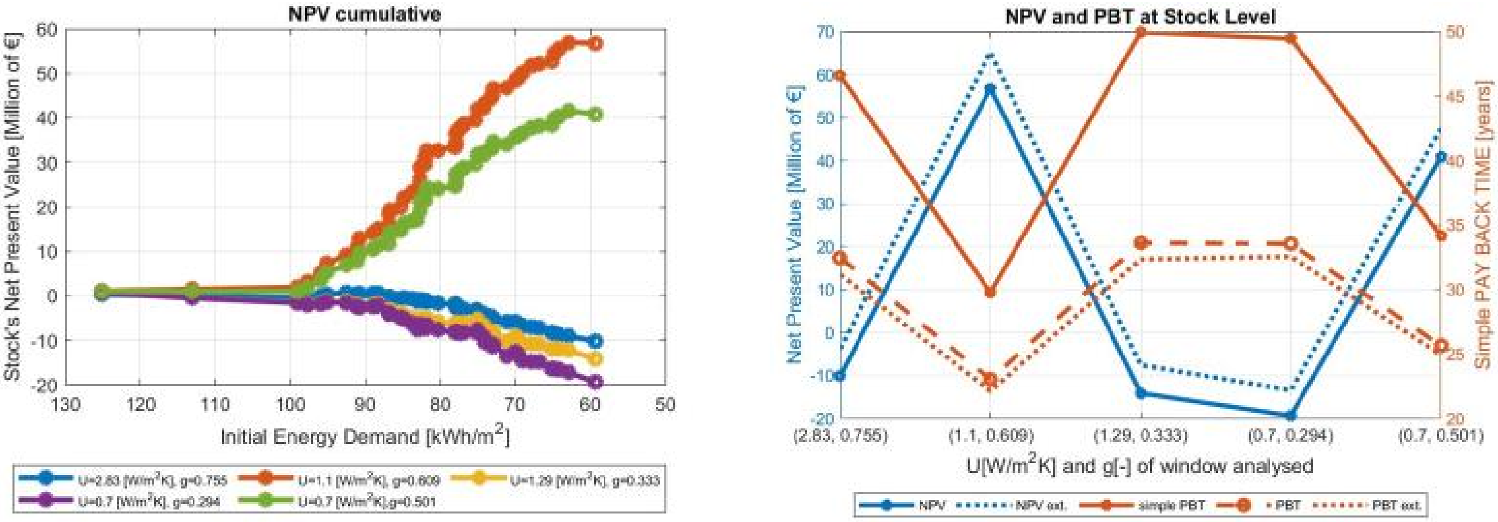


Figure 37 WINDOWS REPLACEMENT: NPV and PBT. On the left, the cumulate of the NPV without considering the externality. On the right, the result obtained when the measure is applied on all the stock: in blue, the NPV with and without considering the externality; in orange the simple PBT, the PBT and the PBT considering the externality.

On the left, Figure 38 shows results related to the differences between the current Investment Cost CI and the Investment cost CI_{PBT10} that ensure a PBT of 10 years; whereas, on the right, the incentives required considering the difference between the CI and the and the CI_{PBT10} are evaluated. As anticipated from the result of Figure 37, the minimum difference between the CI and the CI_{PBT10} is registered for the window that produces the maximum NPV and accounts for 80 €/m^2, which produces a need of incentives equal to 80 Million of € if the government wants to apply the measure in all the buildings of the stock (that have a single plan window) and ensures an average payback time of years to the privates.

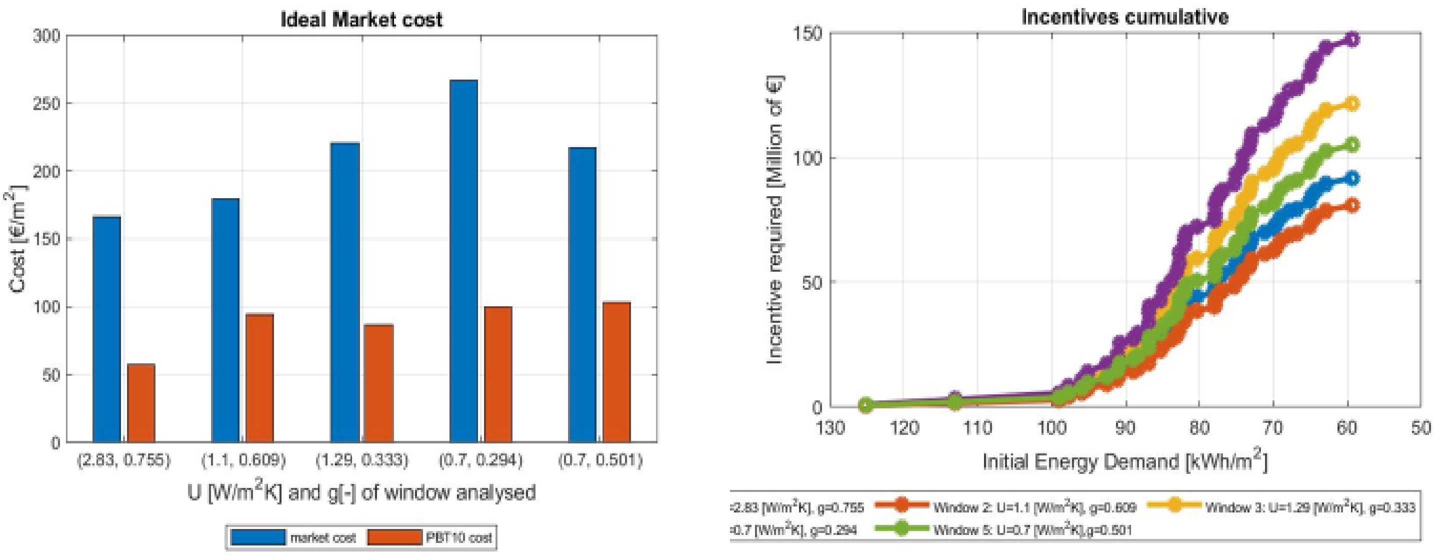


Figure 38 WINDOWS REPLACEMENT: CI_{PBT10} and INCENTIVES. On the left, the comparison between the CI and CI_{PBT10} for the different configuration of windows. On the right, the cumulative of the Incentives indicator.

3.4.3.2 Roof Insulation

The Roof Insulation of the Stock is applied in all the building, starting from the ones with high energy demand according to what exposed in section 2.2 of the methodology. Overall, according to Table 13, four thickness of insulations are analysed as reported in Table 17.

Table 17: Measure Analysed for the roof

Type of insulation	Thickness [cm]	Investment Cost [€/m^2]
Poor Insulation	7	72
Standard Insulation	15	80
Medium Insulation	23	88
Deep Insulation	30	95

Regarding the technological analysis, the first indicator obtained is the PES, differentiated for cooling, heating and total share.

Results related to the cooling share, shown in Figure 39, do not reveal a well-defined trend. This behaviour is due to the simultaneous presence of two phenomenon: the attitude to reduce the night free cooling and the reduction of the inside surface temperature of the ceiling. The sum of these two contrasting effects produces, however, quantitative values of scarce interest for all the four configurations by the moment that affect the cooling energy demand of the building in term of ±1 %.

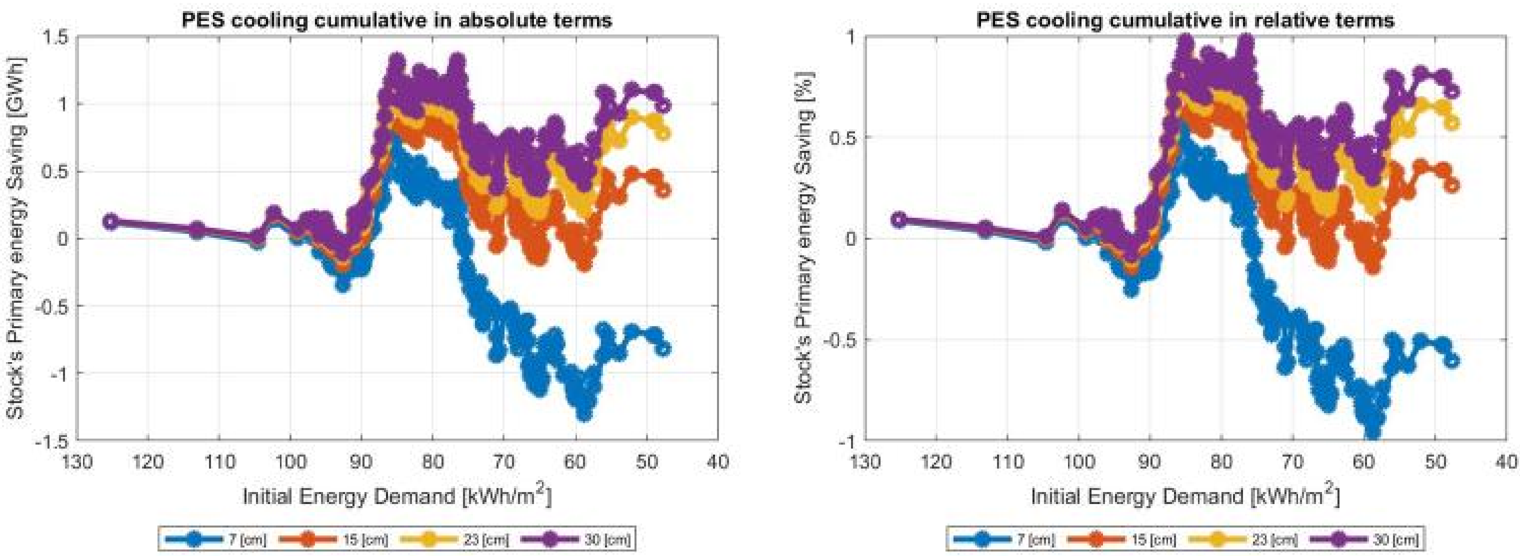


Figure 39 ROOF INSULATION: PES INDICATOR, COOLING SHARE. On the right, the indicator in relative value; on the left the indicator in absolute value.

Focusing on the heating share, results are shown in Figure 40. The PES obtained with deep, medium and standard insulation is almost the same and accounts for 200 GWh, equal to roughly 16% of the total heating ED of the stock. However, the PES reached with poor insulation also obtained good performances as it is 2-3% different from the other configurations.

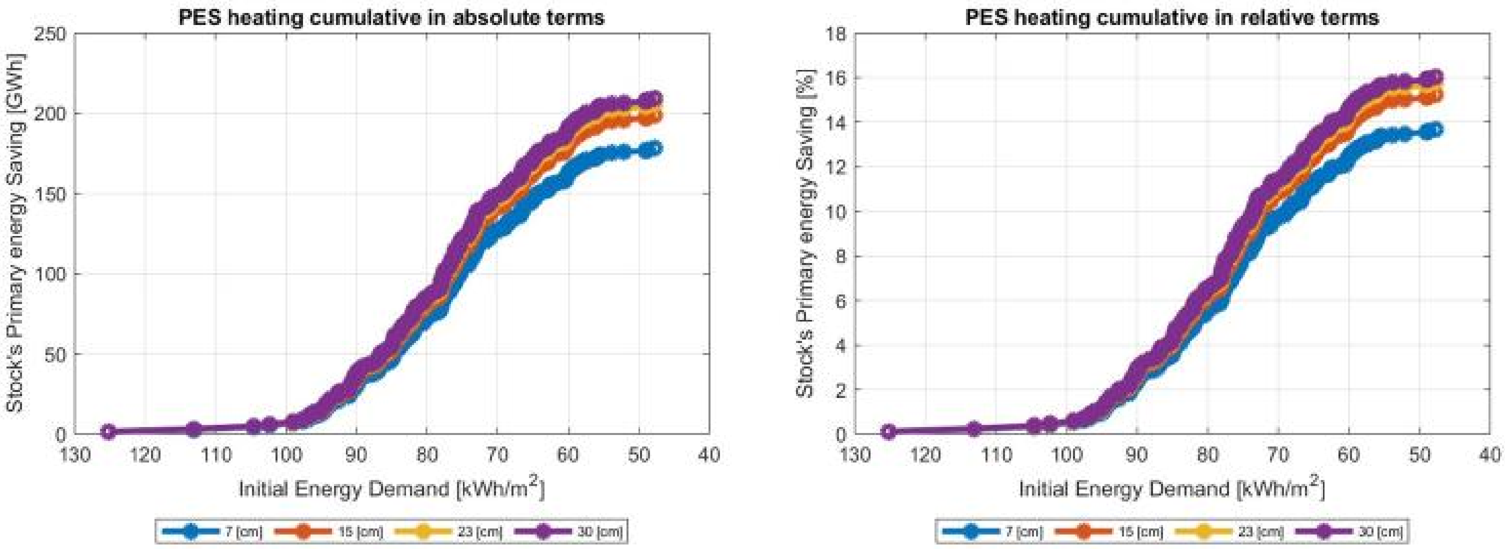


Figure 40 ROOF INSULATION: PES INDICATOR, HEATING SHARE. On the right, the indicator in relative value; on the left the indicator in absolute value.

Finally, the result about the total share, shown in Figure 41, shows the configuration that ensures the best performance along all the year. As the presence of insulation produces negligible effect during the cooling period, the trends are the same as those seen in Figure 40.

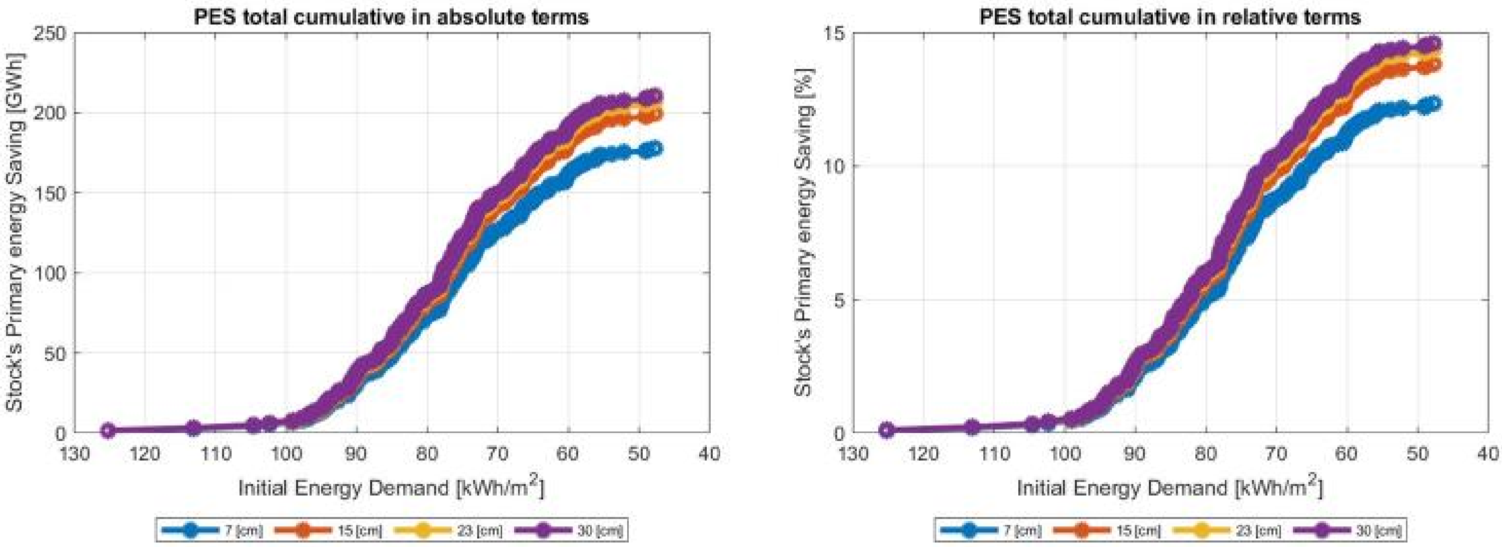


Figure 41 ROOF INSULATION: PES INDICATOR, TOTAL SHARE. On the right, the indicator in relative value; on the left the indicator in absolute value.

Regarding the Carbon energy savings, results are reported in Figure 42, Figure 43 and Figure 44 and account respectively for the cooling, heating and total share. Contrary to what happens for the window retrofit, the performances of the solutions are the same of those seen for the total PES as the cooling PES produced during the cooling period is negligible. Indeed, the CES obtained with deep, medium and standard insulation is almost the same and accounts for 14% of the total ED of the Stock; whereas, the CES reached with poor insulation obtained good performed of 1-2% lower than the other configurations.

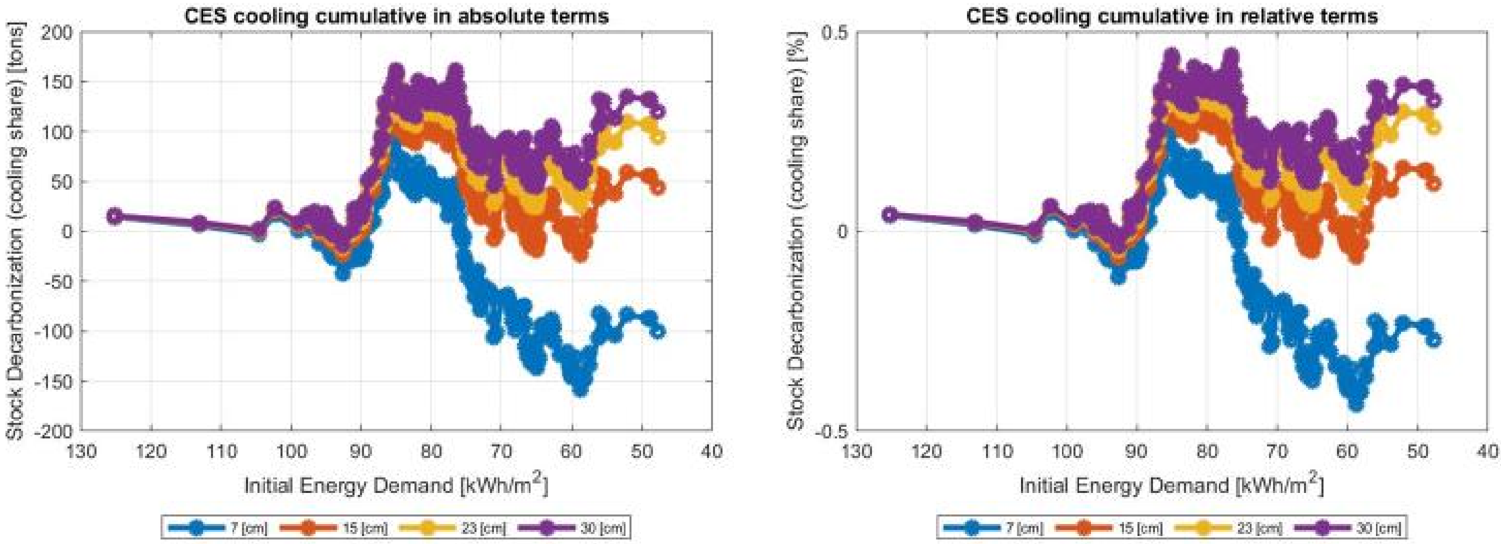


Figure 42 ROOF INSULATION: CES INDICATOR, COOLING SHARE. On the right, the indicator in relative value; on the left the indicator in absolute value.

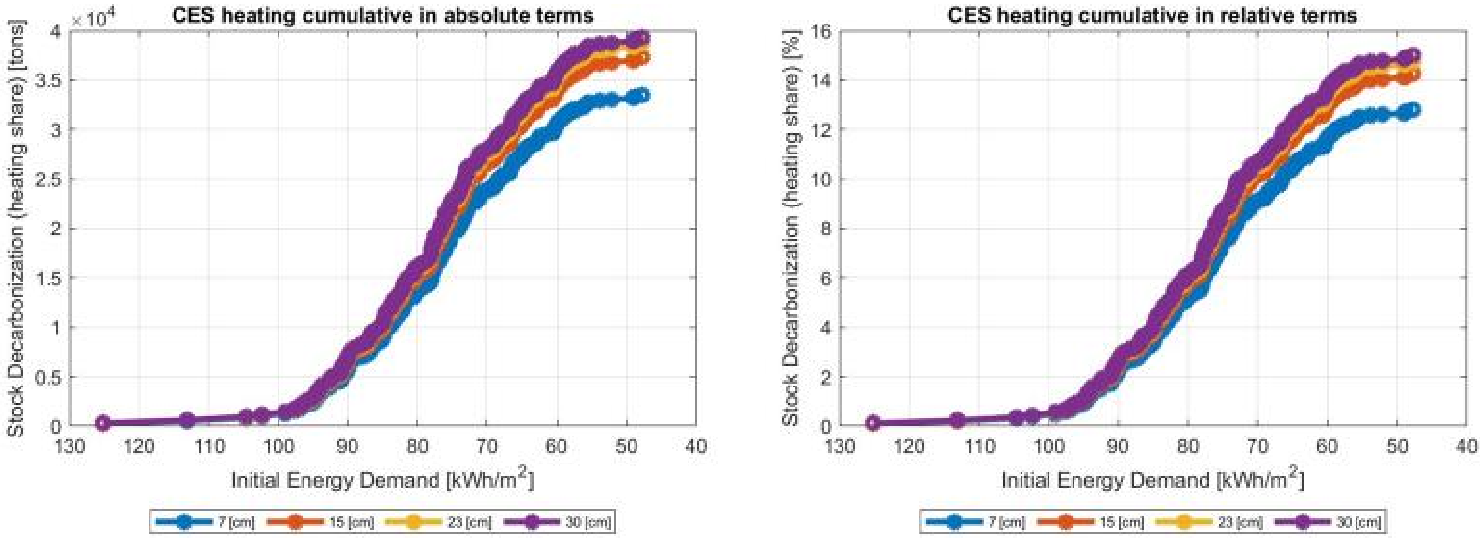


Figure 43 ROOF INSULATION: CES INDICATOR, HEATING SHARE. On the right, the indicator in relative value; on the left the indicator in absolute value.

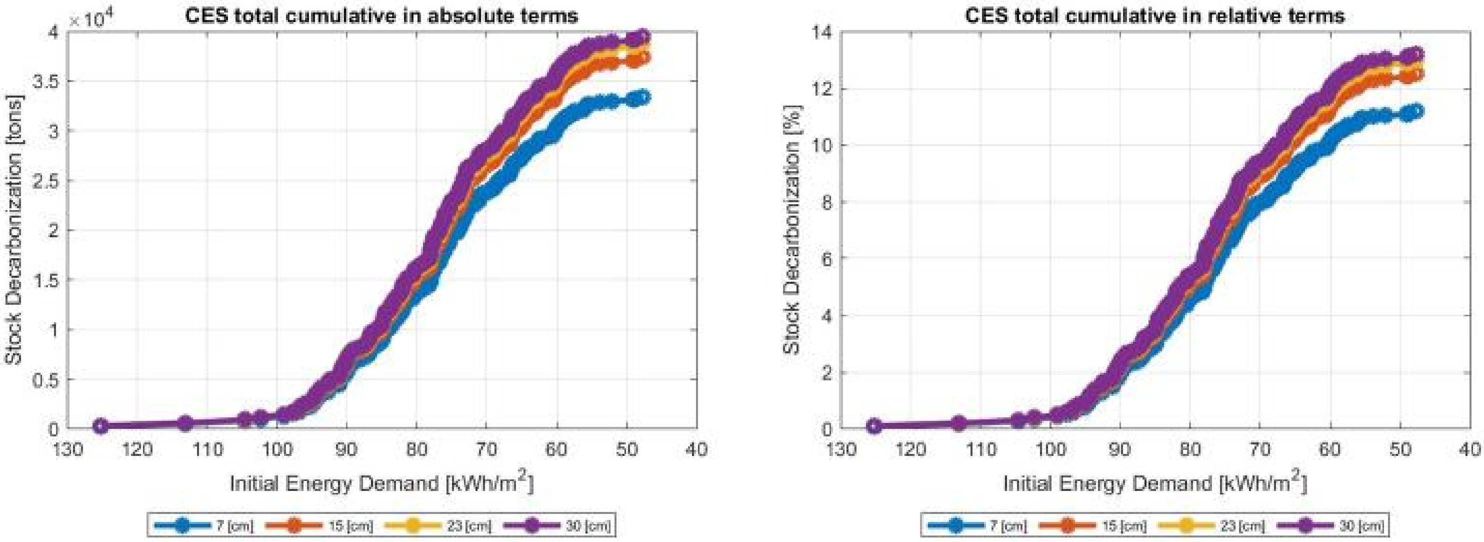


Figure 44 ROOF INSULATION: CES INDICATOR, TOTAL SHARE. On the right, the indicator in relative value; on the left the indicator in absolute value.

The last indicator evaluated within the technical analysis framework is the Power Peak Saving in MW. Regarding the Cooling share, results are shown in Figure 45. Contrary to what happened for the PES and CES, the PPS of the cooling share shows a clear trend since it is not immediately affected by night cooling. As the transmittance of the roof decreases with the insulation thickness, the maximum PPS is reached with the deep insulation and accounts for 5MW, which is equal to roughly 3.5% of the total Peak Power Demand of the Stock; whereas, the relative PPS reached with the poor insulation is about3% different from the deep one.

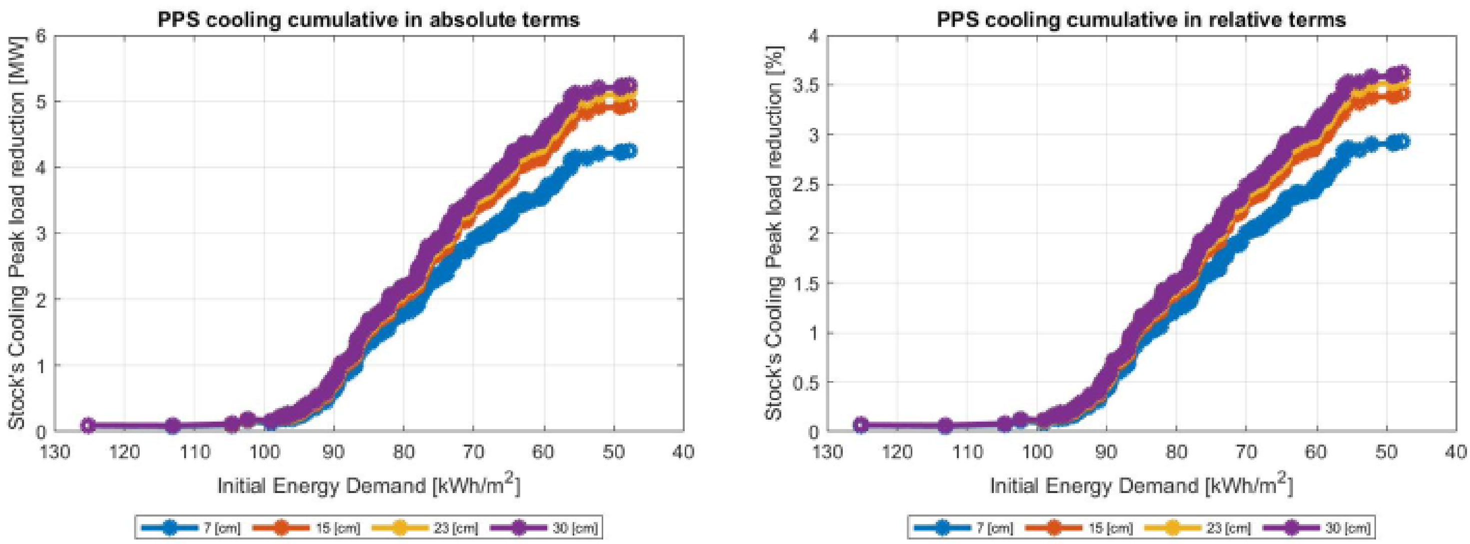


Figure 45 ROOF INSULATION: PPS INDICATOR, COOLING SHARE. On the right, the indicator in relative value; on the left the indicator in absolute value.

Focusing on the heating share, results are shown in Figure 43. Although the trends are the same as those in Figure 45, the effect produced is around three times higher. Indeed, with deep insulation, it can be of 9,5% Peak Power Demand of the Stock, namely, 100MW. However, the relative PPS reached with the poor insulation differs of only 1,5% from the deep one.

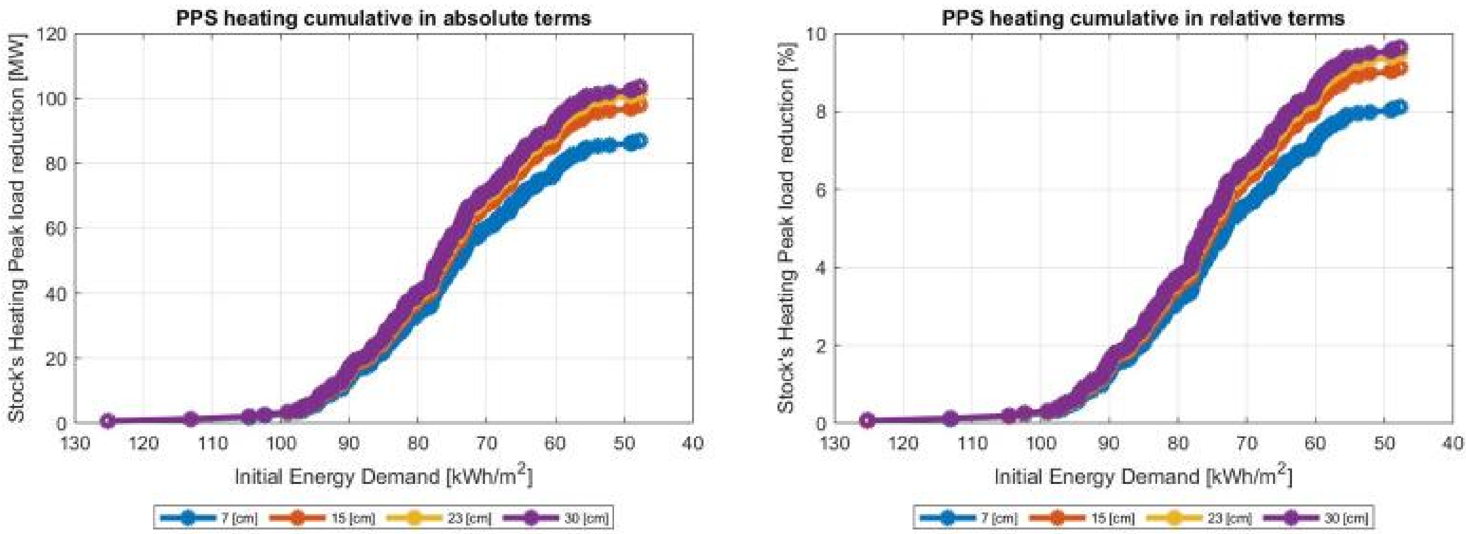


Figure 46 ROOF INSULATION: PPS INDICATOR, HEATING SHARE. On the right the indicator in relative value; on the left the indicator in absolute value.

After analysing the Technological indicators, the Economic performances of the solution are evaluated through the economic indicators**.** Figure 47 illustrates the results regarding the NPV and PBT indicators. Oppositely with the windows case study, all the configurations produced a positive NPV across the building as the slope of the curve is always negative. However, a decreasing of the slope is observed across the last building, as the initial energy efficiency of the building was higher than the other ones. In details, the NPV reached with the thickness of insulation within a range of [15;30] cm does not variate significantly and accounts for about 280-300 million of €. On the other hand, as the price increases linearly with the insulation thickness, the PBTwill change in a non-linear way. Indeed, taking into account the figure on the right, the standard configuration can ensure the lowest PBT period, accounting for an average PBT of 16 years and, therefore, reach the best economic performances among the solutions analysed.

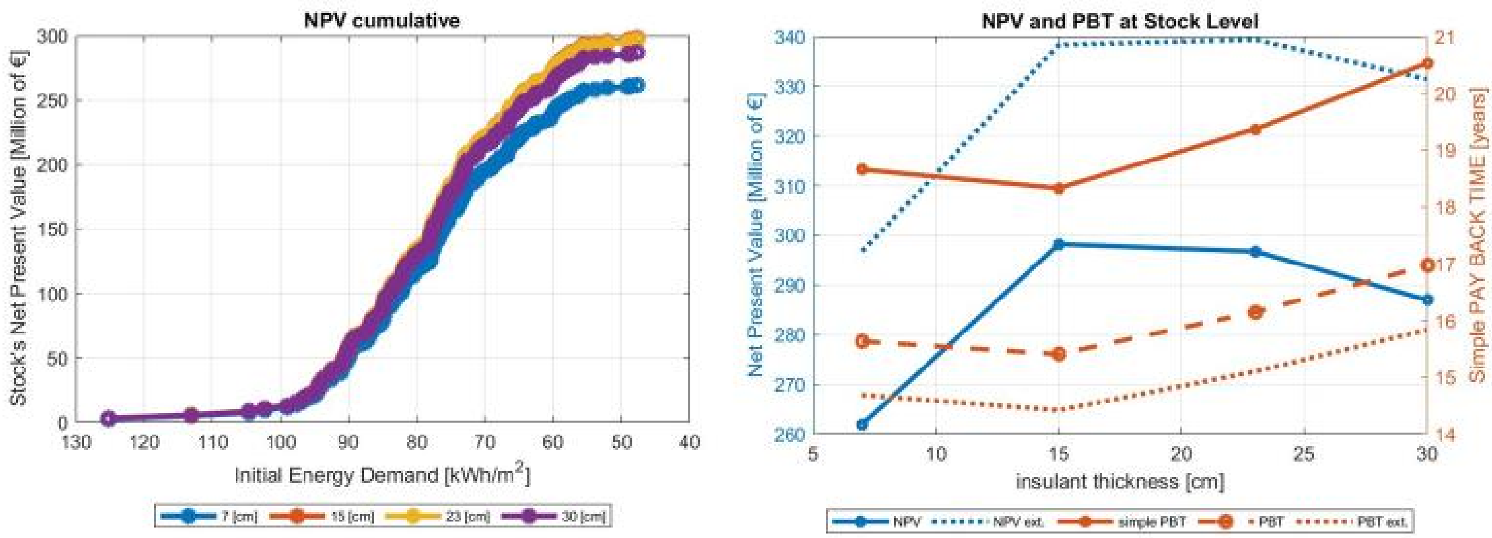


Figure 47 ROOF INSULATION: NPV and PBT. On the left the cumulate of the NPV without considering the externality. On the right the result obtained when the measure is applied on all the stock: in blue, the NPV with and without considering the externality; in orange the simple PBT, the PBT and the PBT considering the externality.

Figure 48 shows results related to the CI_{PBT10} and the Incentives. As anticipated from the result of Figure 47, the minimum difference between the CI and the CI_{PBT10} is registered for standard insulation solution and accounts for 10 €/m^2. This solution produces a need of incentives equal to 80 Million of € if the government wants to apply the measure in all the buildings of the stock (that have a single plan window) and ensure an average payback time of years to the privates. Moreover, it is interesting to notice that the Incentives required by the poor insulation are lower.

This latter behaviour is due to the fact that the poor insulation produces better economic performances than the standard one when applied to the most efficient buildings of the stock.

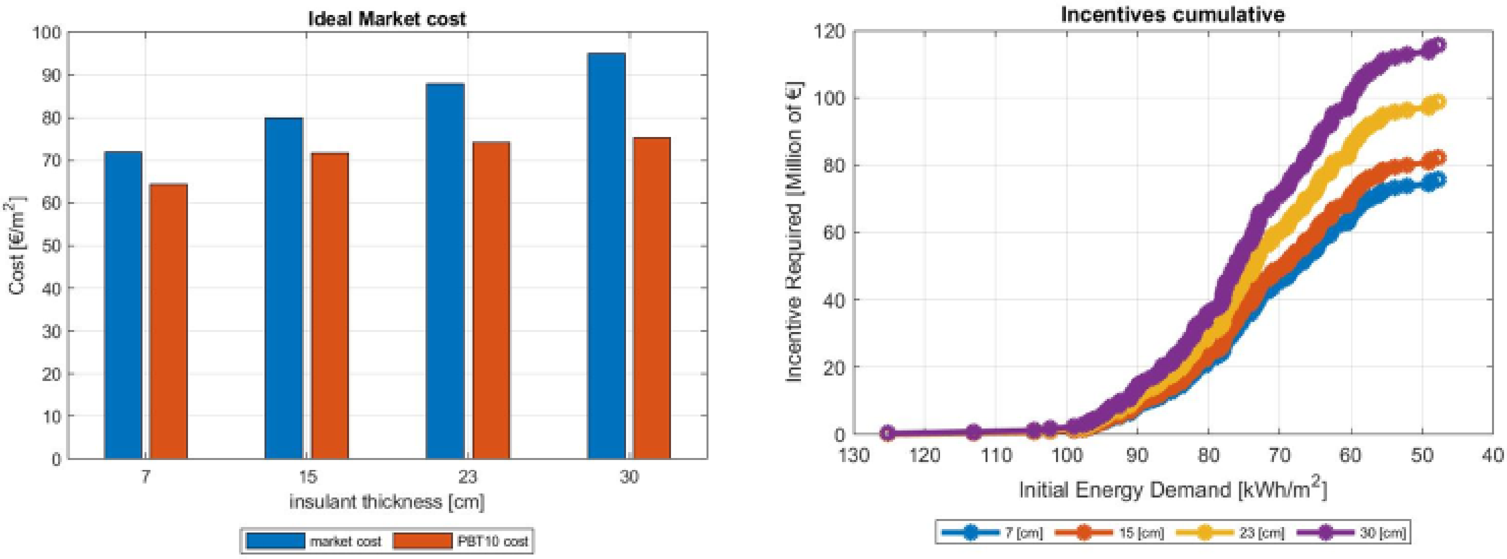


Figure 48 ROOF INSULATION: CI_{PBT10} and INCENTIVES. On the left the comparison between the CI and CI_{PBT10} for the different configuration of windows. On the right, the cumulative of the Incentives indicator.

3.4.3.3 External wall Insulation

The external wall Insulation of the Stock consists of applying a layer of the insulant on the outside part of the wall. The measure is applied in all the building, starting from the ones with a high energy demand according to what exposed in the section 2.2 of the methodology. Overall, according to Table 13, four thicknesses of insulation are analysed as reported in Table 18.

Table 18: Measure Analysed for the External wall

Type of insulation	Thickness [cm]	Investment Cost [€/m^2]
Poor Insulation	5	75
Standard Insulation	10	120
Medium Insulation	15	165
Deep Insulation	20	210

Regarding the Technological analysis, the first indicator obtained is the PES, differentiated for cooling, heating and total share.

Results related to the Cooling share, shown in Figure 49, reveal the presence of a well-defined trend in contrast with what happened in Figure 39. This behaviour is due to the fact that the reduction of the night free cooling is prevalent respect of the reduction of the interior surface temperature achieved by reducing the roof transmittance. Indeed, the PES is negative across all the building by the moment that the shape of the PES's cumulate is always negative. In detail, the reduction of Night free cooling is as high as thicker is the insulation layer, causing negative PES of about 50% for the deep insulation case.

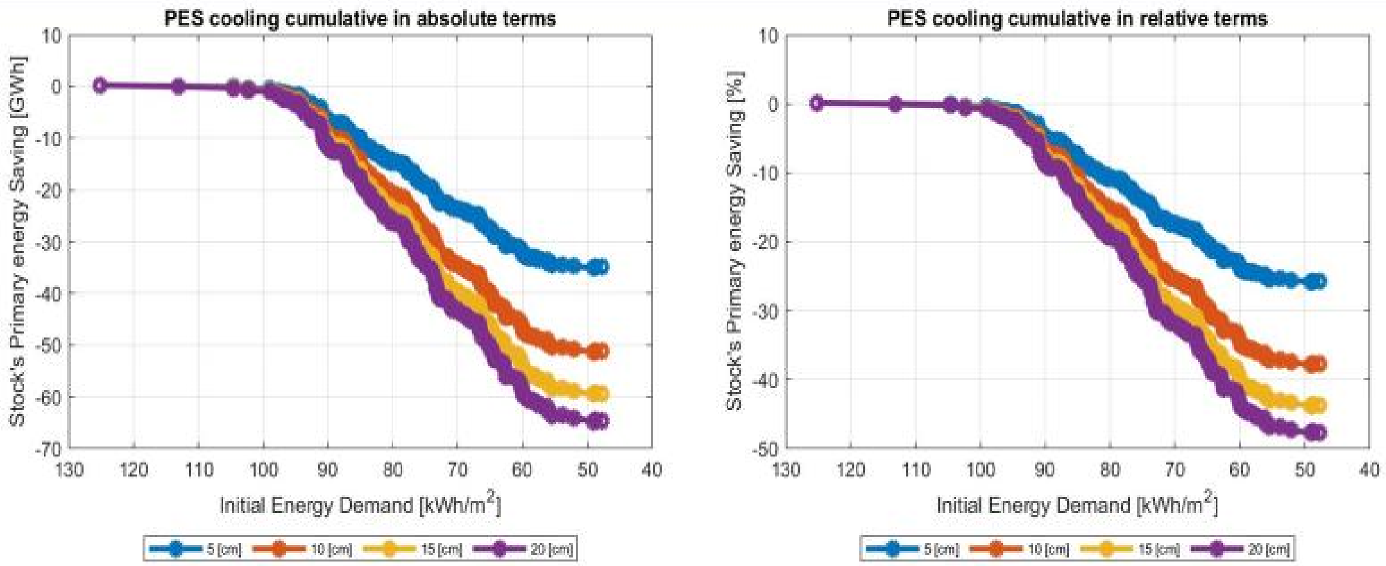


Figure 49 EXTERNAL WALL INSULATION: PES INDICATOR, COOLING SHARE. On the right, the indicator in relative value; on the left the indicator in absolute value.

Focusing on the heating share, results are shown in Figure 50. The PES obtained with deep insulation account for 700 GWh, equal to roughly 55% of the total ED of the Stock, almost 40% higher than what obtained with 20cm of roof insulation in Figure 40. However, also the PES reached with standard insulation obtained good performances as it differs 10-15% from the medium and deep insulation cases. This latter peculiarity will ensure an economic advantage for the standard insulation configuration by the moment that the price per square meter decreases linearly with the thickness.

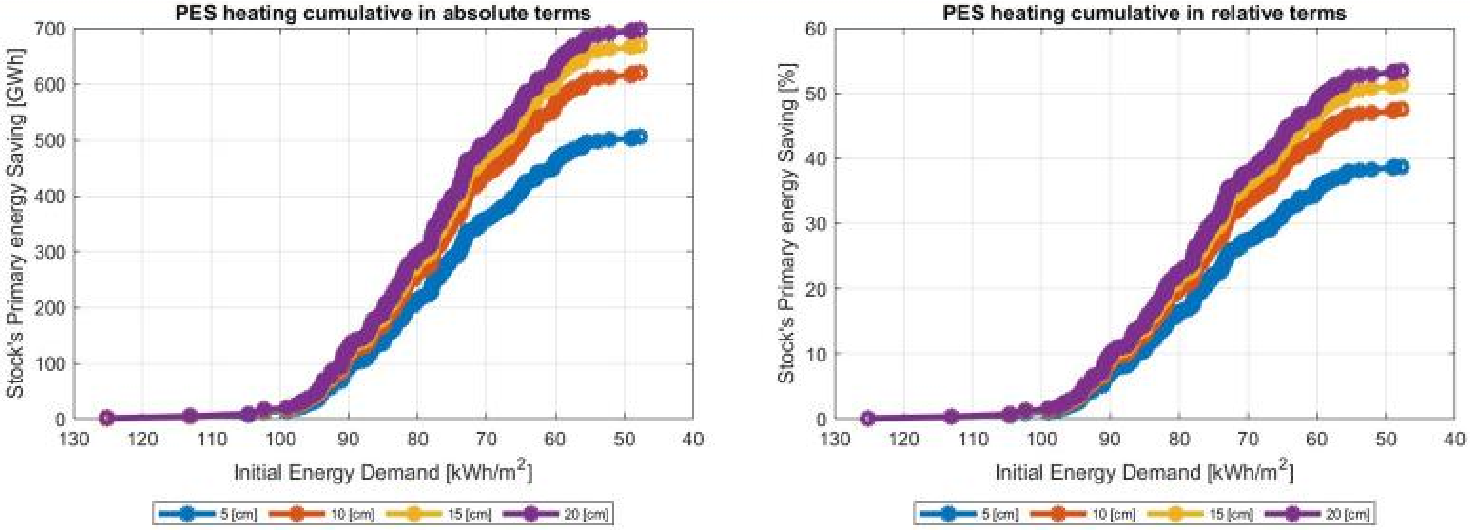


Figure 50 EXTERNAL WALL INSULATION: PES INDICATOR, HEATING SHARE. On the right the indicator in relative value; on the left the indicator in absolute value.

Finally, the result about the total share in Figure 51 shows the configurations that ensure the best performance all along the year. In difference to the observation in the Roof retrofit in Figure 41, the presence of insulation produces a non-negligible effect during the cooling period; therefore the quantitative values are lower than the ones in Figure 50, even though the trends are maintained.

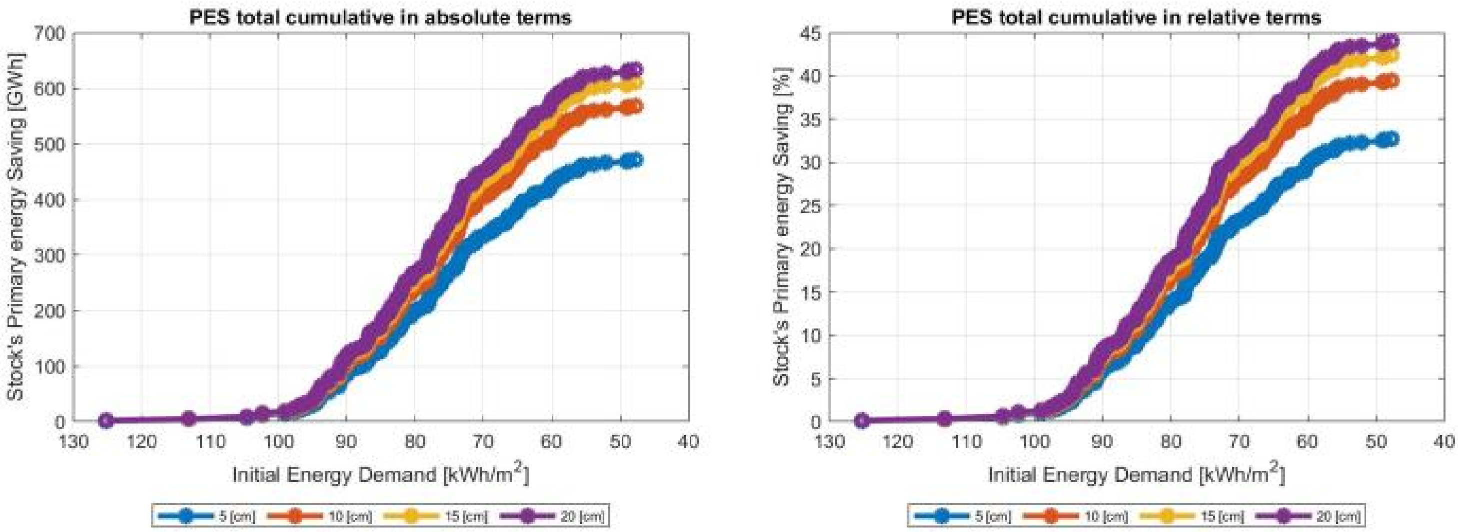


Figure 51 EXTERNAL WALL INSULATION: PES INDICATOR, TOTAL SHARE. On the right the indicator in relative value; on the left the indicator in absolute value.

Regarding the Carbon energy savings, results are reported in Figure 52, Figure 53 and Figure 54 account respectively for the cooling, heating and total share. Regarding the total share, the relatives' values differ from the ones in Figure 51 because the PES obtained during the cooling produces a greater CES due to the electricity saving. Indeed, the CES obtained with deep account for almost 40% of the total CO_2 produced, whereas the relative PES reached are about 45%.

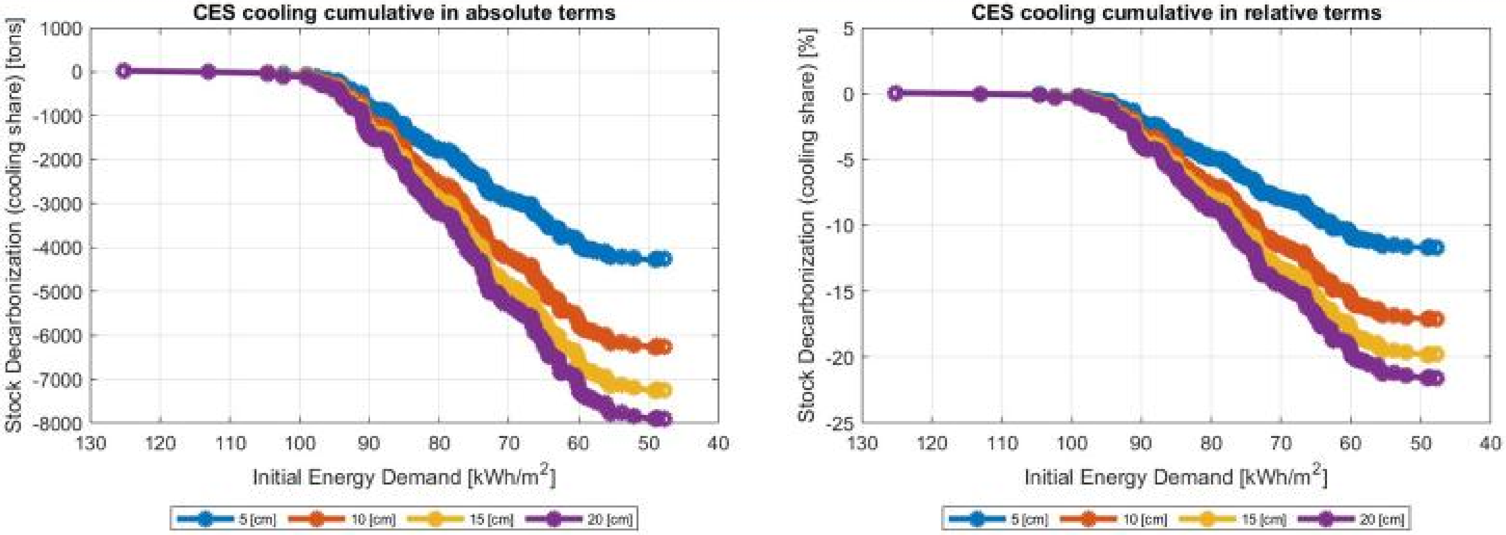


Figure 52 EXTERNAL WALL INSULATION: CES INDICATOR, COOLING SHARE. On the right, the indicator in relative value; on the left the indicator in absolute value.

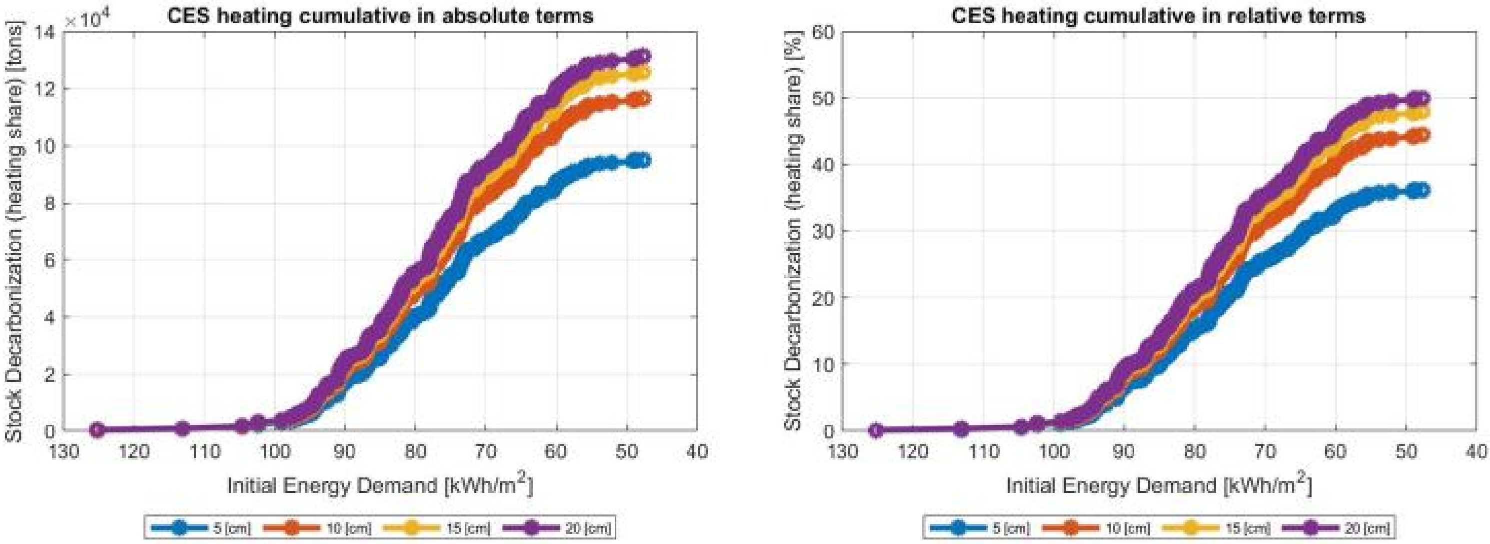


Figure 53 EXTERNAL WALL INSULATION: CES INDICATOR, HEATING SHARE. On the right, the indicator in relative value; on the left the indicator in absolute value.

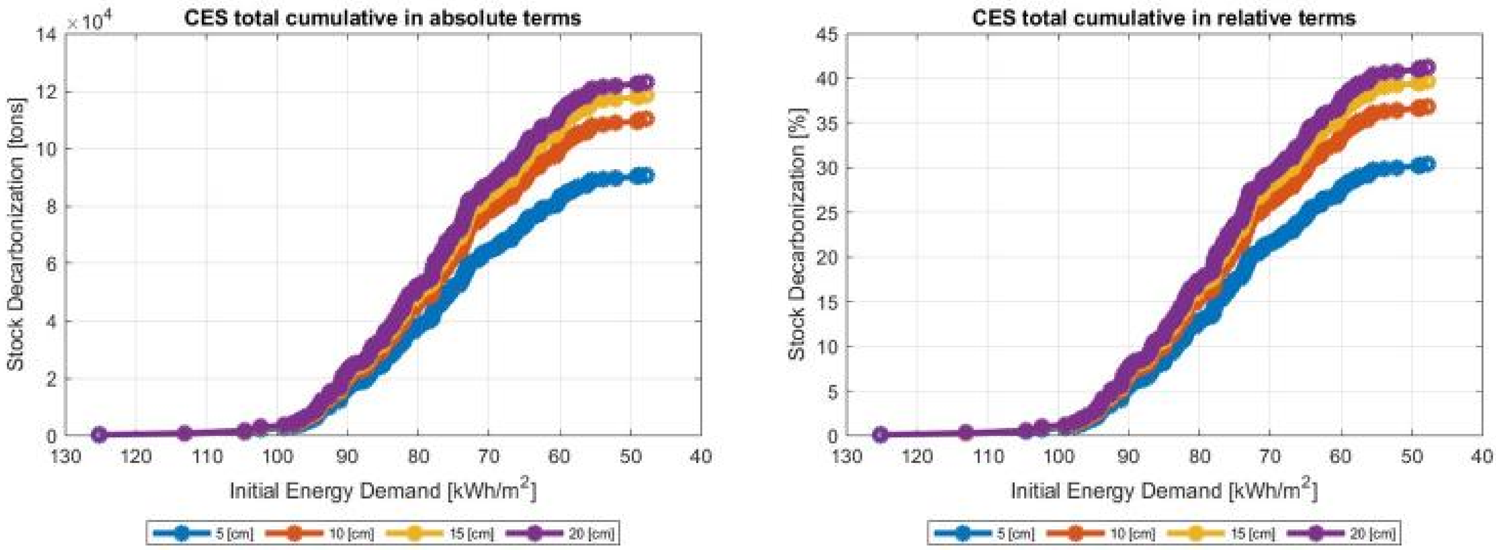


Figure 54 CES INDICATOR, TOTAL SHARE. On the right, the indicator in relative value; on the left the indicator in absolute value.

The last indicator evaluated within the technical analysis framework is the Power Peak Saving in MW. Regarding the Cooling share, results are shown in Figure 55. As the transmittance of the roof decreases with insulation thickness, the maximum PPS is reached with the deep insulation and accounts for 15MW, which is equal to roughly 10% of the total Peak Power Demand of the Stock; whereas, the relative PPS reached with the poor insulation differs of about 3% from the deep one. It is notable that, although the insulated surface has increased respect to the Roof Insulation, the results variate of less than 7% respect to those in Figure 45.

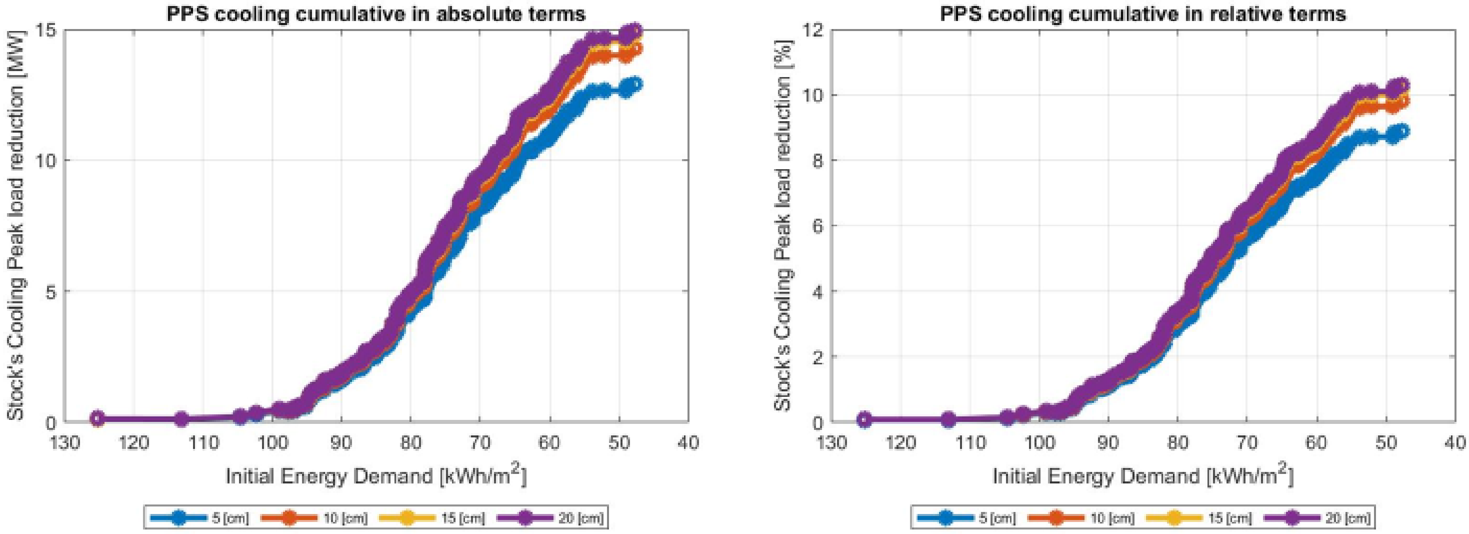


Figure 55 EXTERNAL WALL INSULATION: PPS INDICATOR, COOLING SHARE. On the right the indicator in relative value; on the left the indicator in absolute value.

Focusing on the heating share, results are shown in Figure 56. Although the trends are the same as those in Figure 55, the effect produced is around four times more significant as also happened for the roof insulation case. Indeed, with deep insulation, it can reduce 37% the Peak Power Demand of the Stock, namely, 400MW.

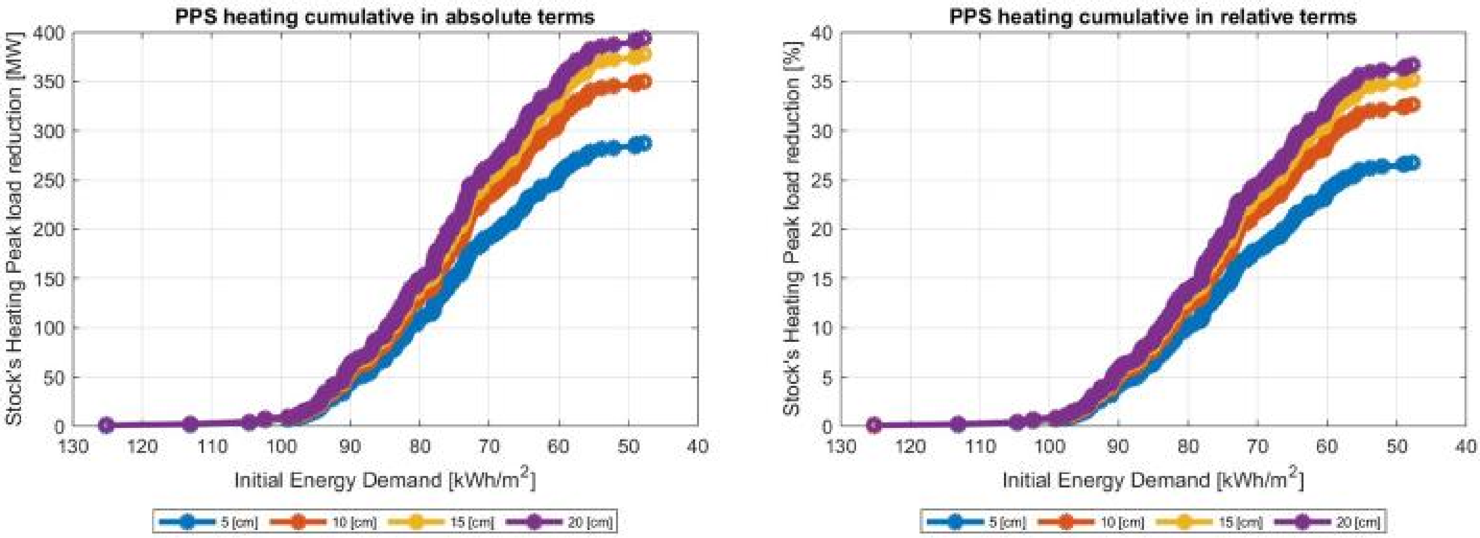


Figure 56 EXTERNAL WALL INSULATION: PPS INDICATOR, HEATING SHARE. On the right, the indicator in relative value; on the left the indicator in absolute value.

Once evaluated the technological effects of the solution, Economic performances are quantified through economic indicators**.** Figure 57 illustrates the results regarding the NPV and PBT indicators. Oppositely with the roof insulation case study, not all the configuration produced a positive NPV across the building. Indeed, only the poor insulation produces a positive global NPV's value. Moreover, the change of the slope means that for building with an initial energy demand minor than 70 kW/m^2 the NPV produced is negative. Therefore, assuming a life span of 30 years, only the buildings with an initial energy demand greater than 70 kW/m^2 produce a positive NPV. According to the NPV results, only the PBT of the poor insulation is about 30 years, whereas the other PBT increase up to 50 years for the deep insulation case.

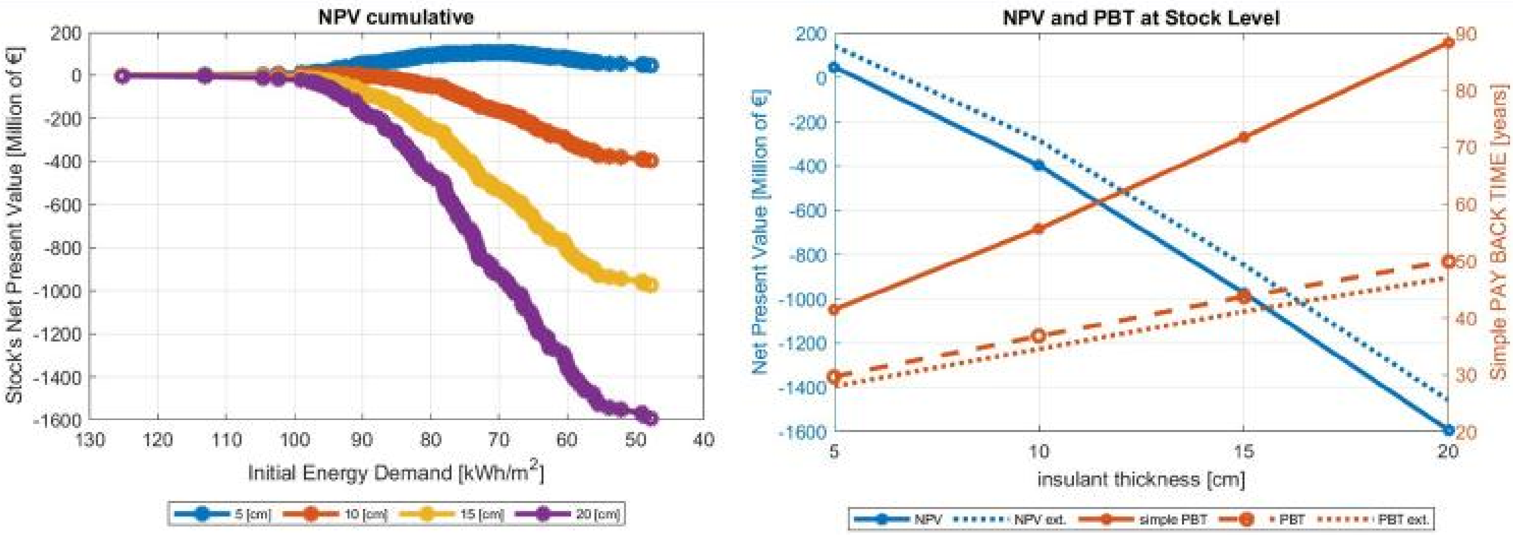
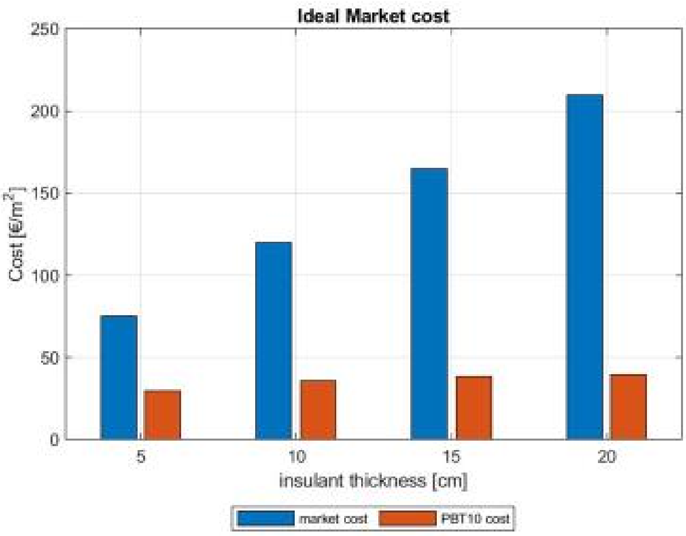


Figure 57 EXTERNAL WALL INSULATION: NPV and PBT. On the left the cumulate of the NPV without considering the externality. On the right the result obtained when the measure is applied on all the stock: in blue, the NPV with and without considering the externality; in orange the simple PBT, the PBT and the PBT considering the externality.

Figure 58 shows results related to the CI_{PBT10} and the Incentives. As anticipated from the result of Figure 47, the minimum difference between the CI and the CI_{PBT10} is registered for poor insulation solution and accounts for 50 €/m^2. This produces a need of incentives equal to 750 Million of € if the government wants to apply the measure in all the buildings of the stock (that have a single plan window) and ensure an average payback time of ten years to the privates.

Moreover, it is notable that the CI_{PBT10} required for the other solutions is almost the same as they reach saturation of the PES effect.



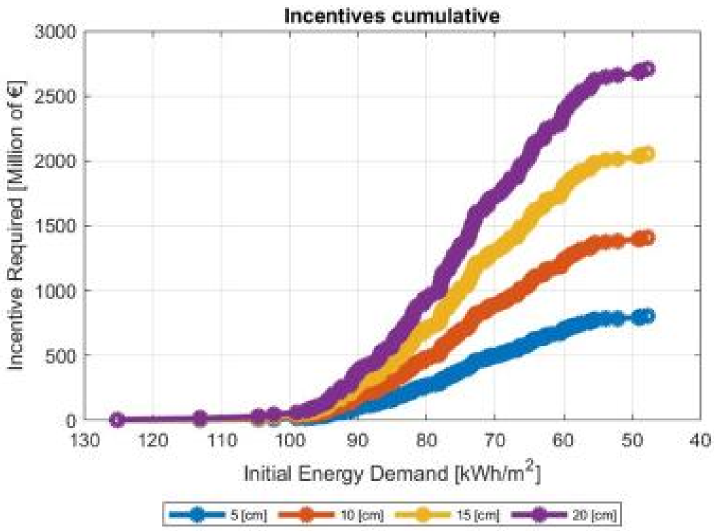


Figure 58 EXTERNAL WALL INSULATION: CI_{PBT10} and INCENTIVES. On the left the comparison between the CI and CI_{PBT10} for the different configuration of windows. On the right, the cumulative of the Incentives indicator.

3.4.3.4 Internal wall Insulation

The internal wall Insulation of the Stock consists of applying a layer of the insulant on the outside part of the wall on all the building, starting from the ones with a high-energy demand according to what exposed in section 2.2 of the methodology. Overall, according to Table 13, four thicknesses of insulation are analysed as reported in Table 19.

Table 19 : Measure Analysed for the Internal wall

Type of insulation	Thickness [cm]	Investment Cost [€/m^2]
Poor Insulation	7	37
Standard Insulation	15	65
Medium Insulation	20	87.5
Deep Insulation	25	100

Regarding the Technological analysis, the first indicator obtained is the PES, differentiated for cooling, heating and total share.

Results related to the Cooling share, shown in Figure 59, reveal an analogy with the trend obtained in Figure 49 with the external wall insulation. However, looking at the values, the growth of the Cooling energy demand caused by the internal insulation is slightly greater than the external insulation case. This behaviour is due to the fact that the positioning of the insulant in the internal layer, beyond reducing the night free cooling, reduces the internal thermal capacity of the façade. In detail, the reduction of night free cooling causes a negative PES of about 55% for the deep insulation case.

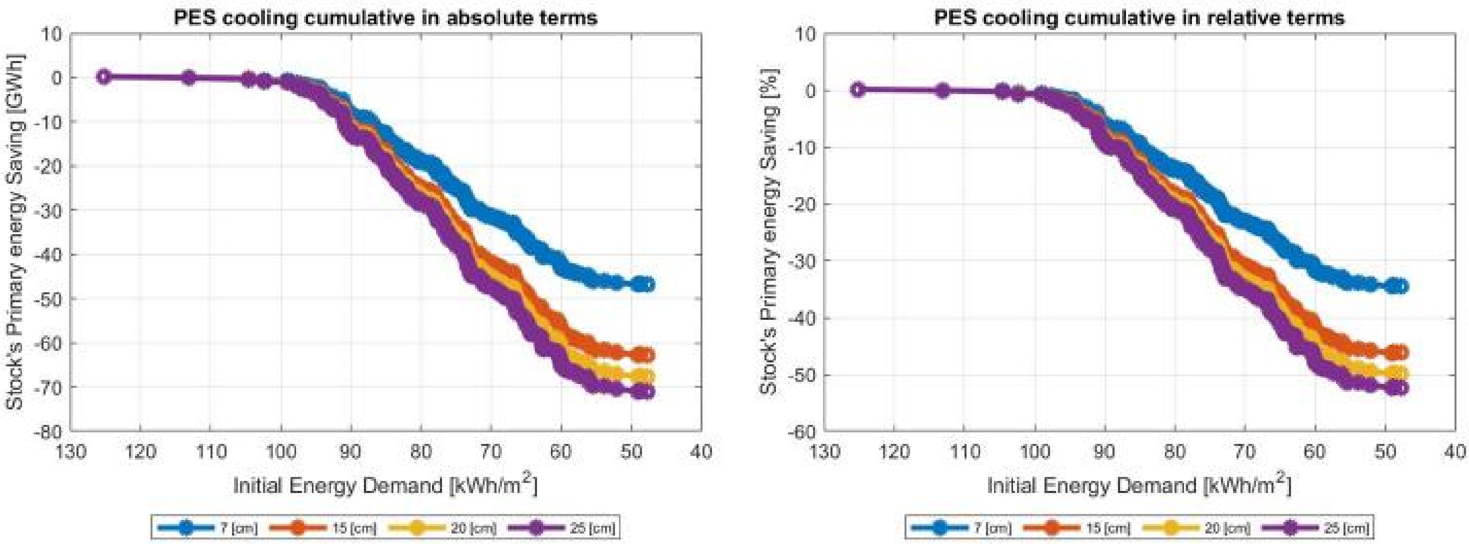


Figure 59 INTERNAL WALL INSULATION: PES INDICATOR, COOLING SHARE. On the right, the indicator in relative value; on the left the indicator in absolute value.

Focusing on the heating share, results are shown in Figure 60, Figure 30. The PES obtained with deep insulation accounts for 700 GWh, equal to roughly 55% of the total ED of the Stock. Moreover, results obtained with the medium insulation case (20cm) are almost 3% lower than those obtained with an equivalent layer of external wall insulation (Figure 50). However, in analogy with the roof and external insulation, also the PES reached with poor insulation obtained good performances as it differs 10-15% from the medium and deep insulation cases. This latter peculiarity will insure a better economic behaviour for the standard insulation configuration by the moment that the price per square meter decreases linearly with the thickness.

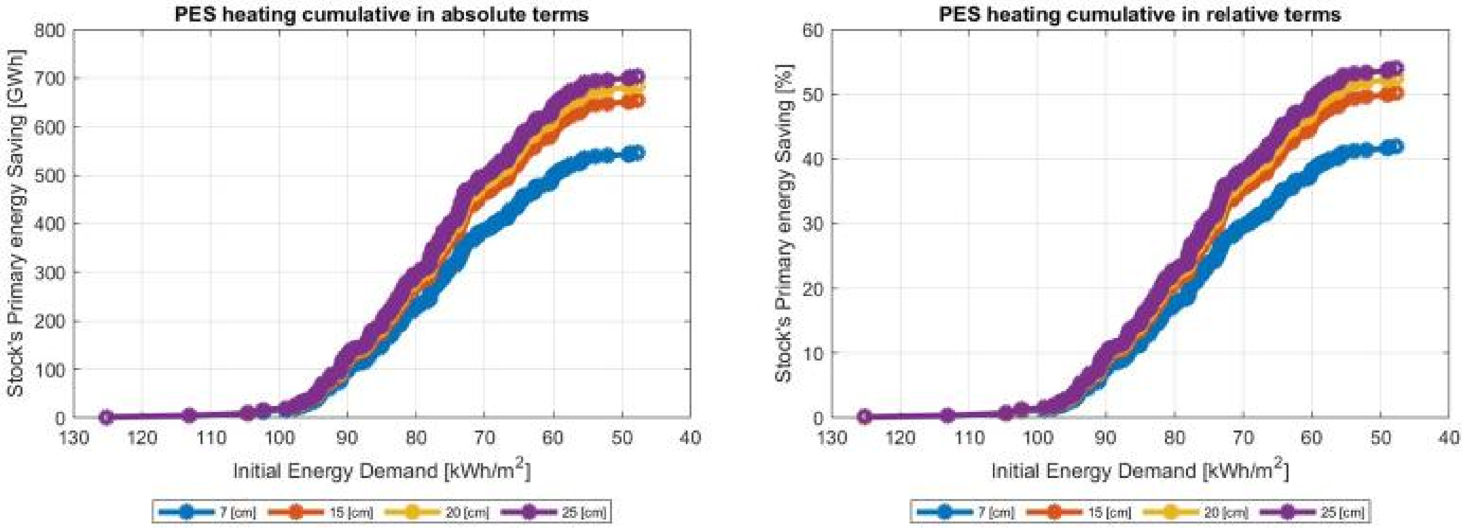


Figure 60 INTERNAL WALL INSULATION: PES INDICATOR, HEATING SHARE. On the right, the indicator in relative value; on the left the indicator in absolute value.

Finally, the result about the total share, shown in Figure 61, defines what the technology configuration that ensures the best performance all along the years is. In analogy with what observed in the external wall retrofit in Figure 51, the presence of insulation produces a non-negligible effect during the cooling period. Therefore, the quantitative values are lower than the ones in Figure 60, even though the trends are maintained.

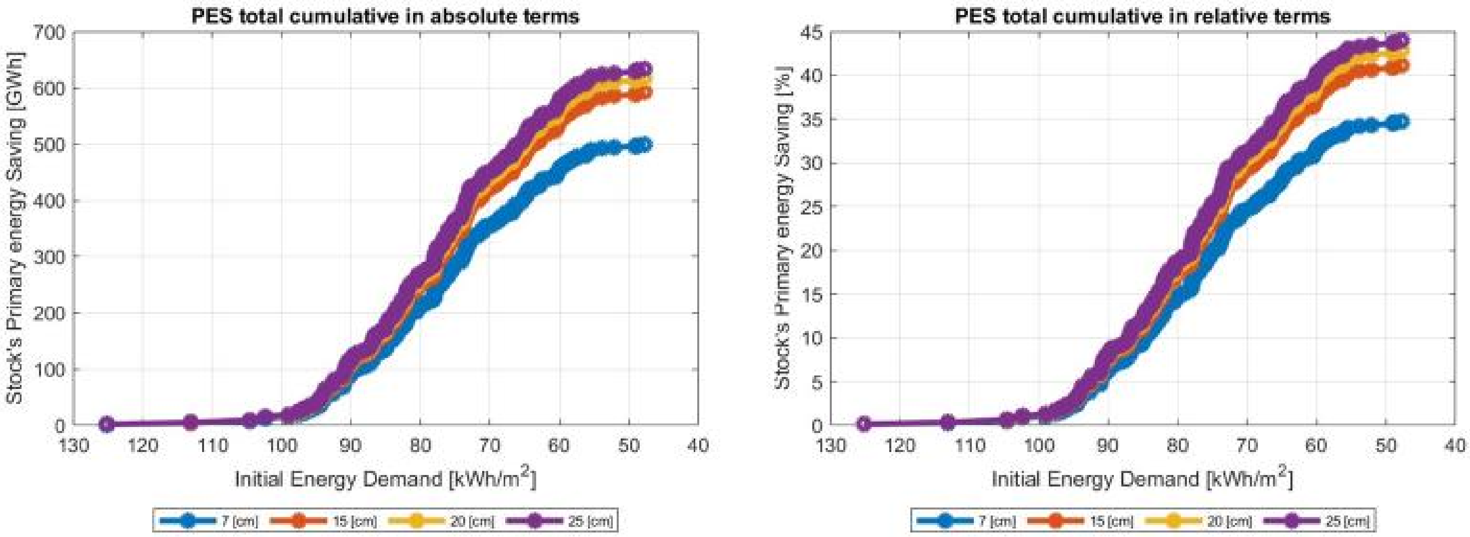


Figure 61 INTERNAL WALL INSULATION: PES INDICATOR, TOTAL SHARE. On the right, the indicator in relative value; on the left the indicator in absolute value.

Regarding the Carbon Energy Saving, results are reported in

Figure 62, Figure 63 and Figure 64 account respectively for the cooling, heating and total share. In analogy with the external wall insulation case, the relatives' values of the total hare differ from the ones in Figure 61 because the PES obtained during the cooling produces a greater CES due to the electricity saving. Indeed, the CES obtained with deep accounts for almost 40% of the total CO_2 produced, whereas the relative PES reached are about 45%.

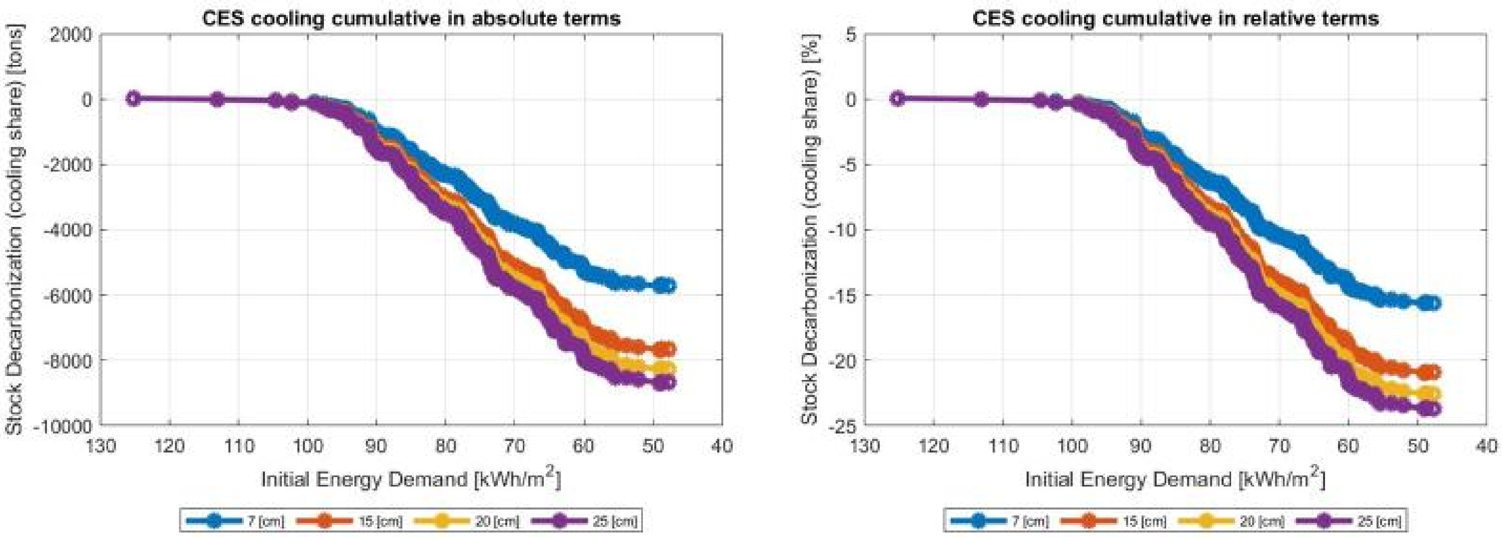


Figure 62 INTERNAL WALL INSULATION: CES INDICATOR, COOLING SHARE. On the right, the indicator in relative value; on the left the indicator in absolute value.

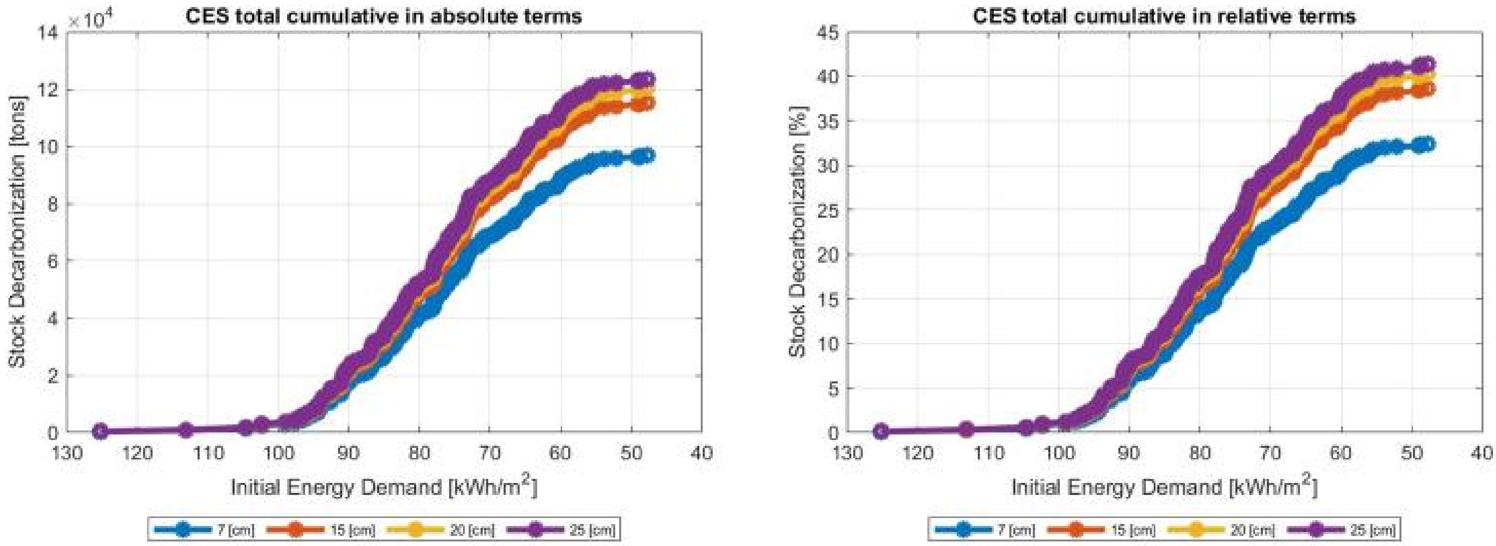


Figure 63 INTERNAL WALL INSULATION: CES INDICATOR, HEATING SHARE. On the right, the indicator in relative value; on the left the indicator in absolute value.

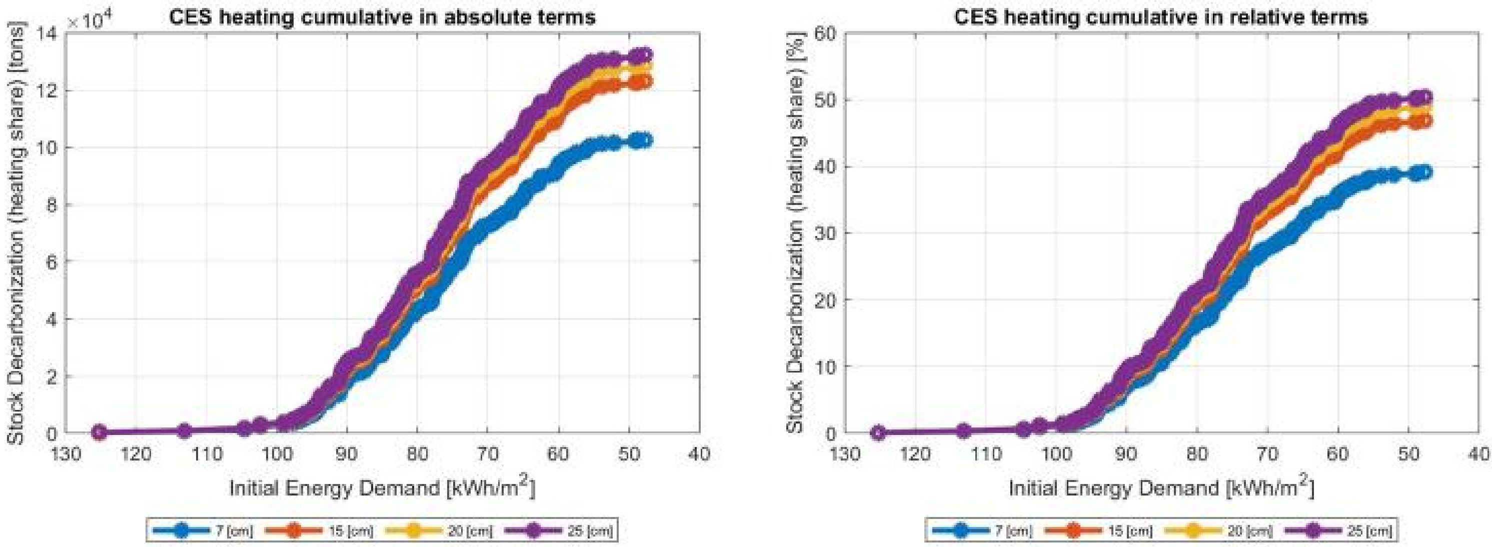


Figure 64 INTERNAL WALL INSULATION: CES INDICATOR, TOTAL SHARE. On the right, the indicator in relative value; on the left the indicator in absolute value.

The last indicator evaluated within the technical analysis framework is the Power Peak Saving in MW. Regarding the Cooling share, results are shown in Figure 65. As the transmittance of the insulant decreases with the thickness, the maximum PPS is reached with the deep insulation and account for 12MW, which is equal to roughly 8% of the total Cooling Peak Power Demand of the Stock. It is notable that the same value is obtained with 5cm of external insulation. Therefore, the external insulation works better in reducing the cooling peak power demand.

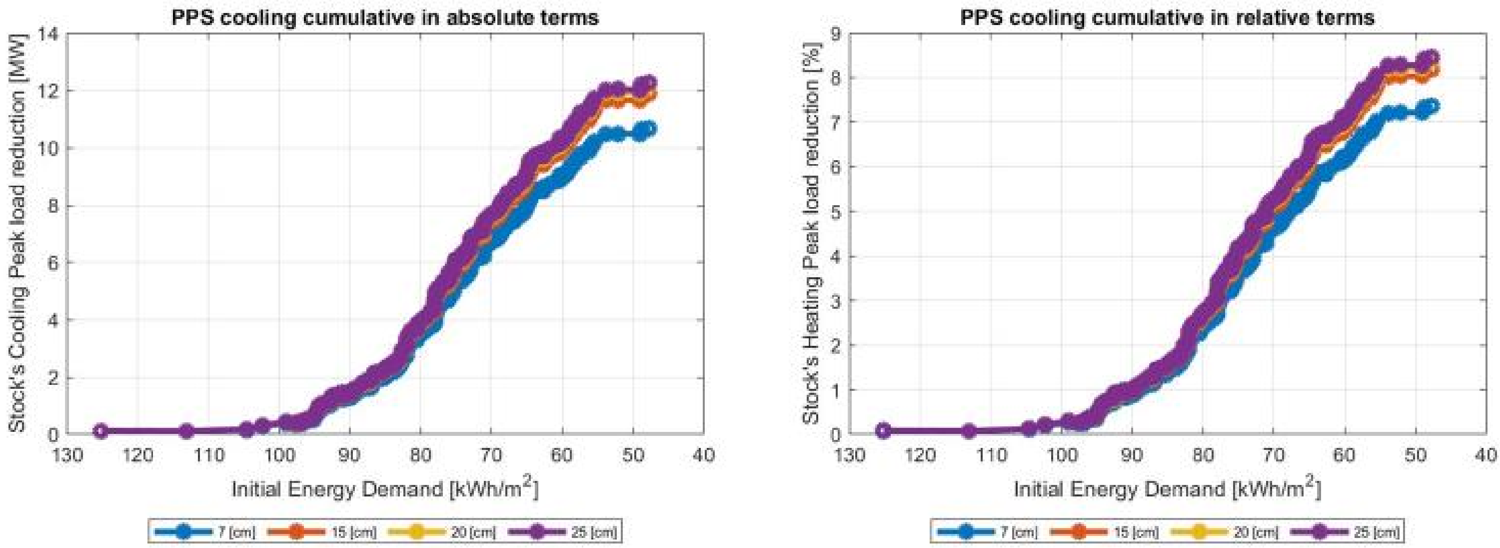
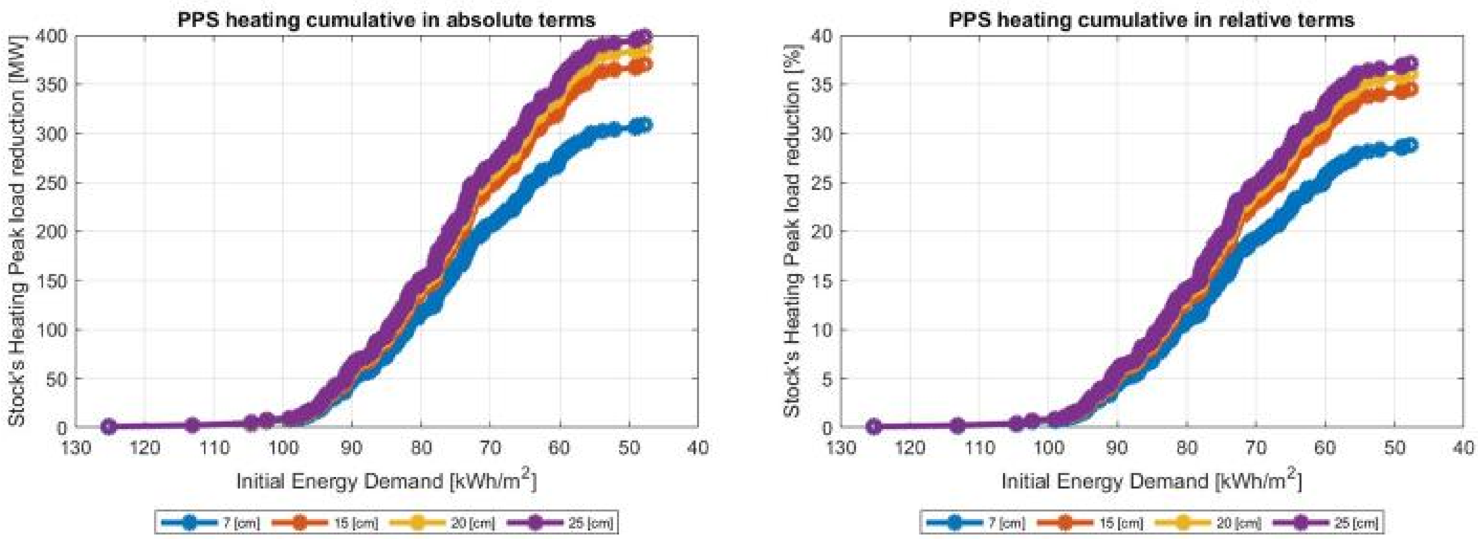


Figure 65 INTERNAL WALL INSULATION: PPS INDICATOR, COOLING SHARE. On the right, the indicator in relative value; on the left the indicator in absolute value.

Focusing on the heating share, results are shown in Figure 66. Although the trends are the same as those in Figure 55, the effect produce is around 20 times more significant as also happened for the roof and external insulation and cases. Indeed, deep insulation can reduce by 35% the Peak Power Demand of the Stock, namely, 400MW. Moreover, it is notable that the results obtained with 20cm of insulant are similar to those obtained with deep external insulation.

Figure 66 INTERNAL WALL INSULATION: PPS INDICATOR, HEATING SHARE. On the right, the indicator in relative



value; on the left the indicator in absolute value.

Successively, once produced the Technological indicators, the Economic performances of the solutions through the economic indicators are evaluated**.** Figure 57 illustrates the results regarding the NPV and PBT indicators. Oppositely with the external wall insulation case study, all the configurations produced a positive NPV across the building. However, a change in the derivate of the cumulative NPV curve is noticeable for the deep and medium insulation cases for buildings with an initial energy demand lower than 70kW/m^2. Therefore, applying medium or deep insulation and assuming a life span of 30 years, only buildings with an initial energy demand greater than 70 kW/m^2 produce a positive NPV. It is notable that the limit of 70kW/m^2 is in analogy with what seen in Figure 57 for the external wall insulation. According to the NPV results, all the PBT are lower than 30 years, with a PBT increase of 17 years for the poor insulation case.

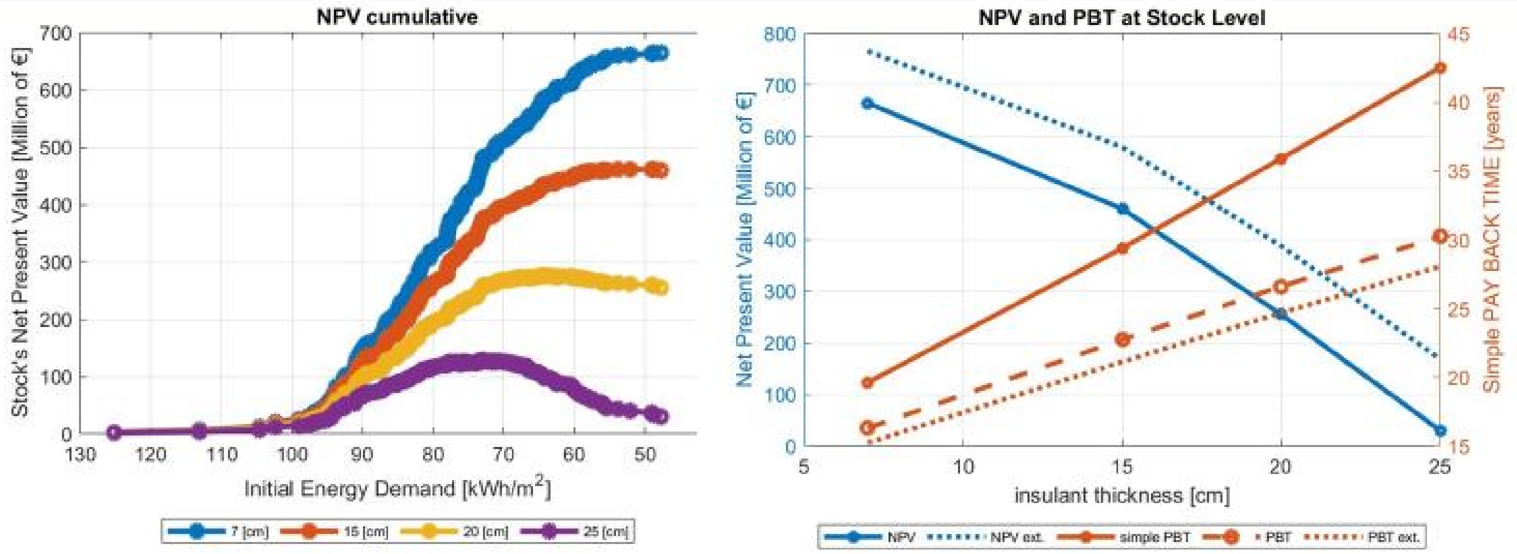


Figure 67 INTERNAL WALL INSULATION: NPV and PBT. On the left the cumulate of the NPV without considering the externality. On the right the result obtained when the measure is applied on all the stock: in blue, the NPV with and without considering the externality; in orange the simple PBT, the PBT and the PBT considering the externality.

Figure 68 shows results related to the CI_{PBT10} and the Incentives. As anticipated from the result of Figure 67, the minimum difference between the CI and the CI_{PBT10} is registered for poor insulation solution and accounts for 7 €/m^2. This solution produces a need of incentives equal to 200 Million of € if the government wants to apply the measure in all the buildings of the stock (that have a single plan window) and ensure an average payback time of ten years to the privates. Moreover, it is notable that the CI_{PBT10} required for the other solutions is almost the same as they reach saturation of the PES effect.

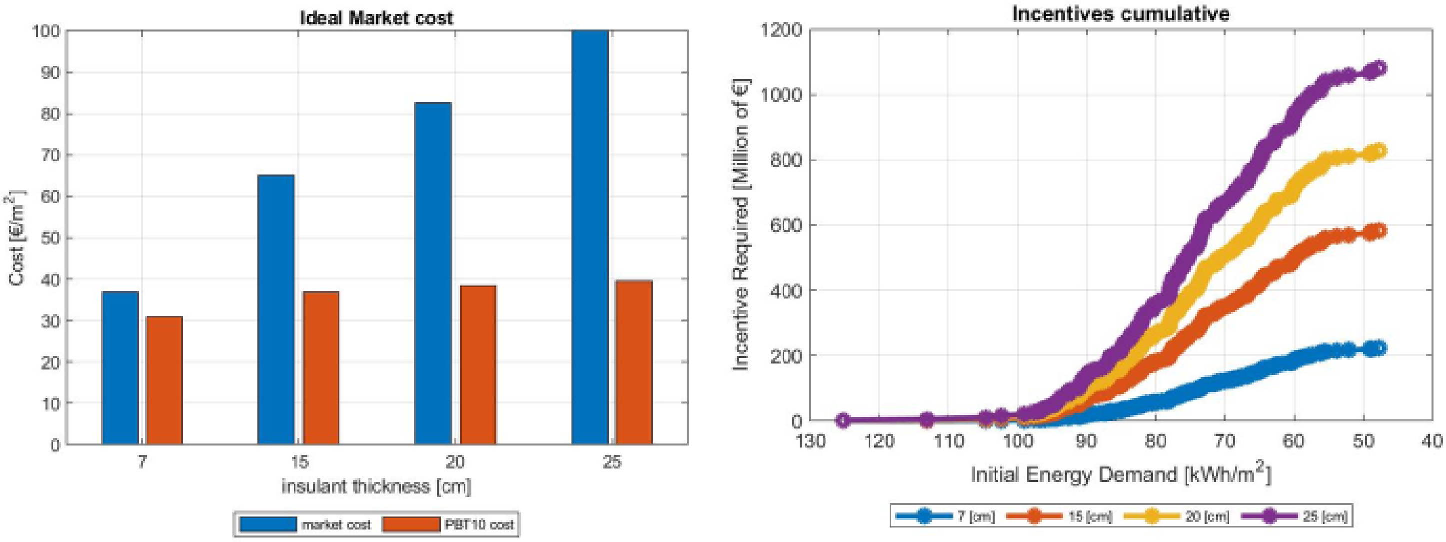


Figure 68 INTERNAL WALL INSULATION: CI_{PBT10} and INCENTIVES. On the left the comparison between the CI and CI_{PBT10} for the different configuration of windows. On the right, the cumulative of the Incentives indicator.

3.4.3.5 System Replacement

The System Replacement consists of comparing three different solutions according to the data in Table 16 and Table 11:

- Boiler (efficiency of 0.91) to supply the heating energy demand;
- Air conditioning split unit (COP of 3.89) to supply the cooling energy demand;
- Heat pump to supply both heating (COP of 4.57) and cooling (COP of 3.57) demand;

The systems are analysed one by one and, in analogy with the other retrofit measures, are applied in all the buildings, starting from the ones with high-energy demand according to what exposed in section 2.2 of the methodology.

Regarding the Technological analysis, the first indicator obtained is the PES, differentiated for cooling, heating and total share. Results related to the Cooling share, shown in Figure 69, reveal a better performance for the air conditioning system because of the greater COP. The overall PES reached with the air conditioning system account for 85 GWh reached accounting for roughly 60% of the total ED of the Stock, whereas the relative PES reached with heat pump system is about 10% lower.

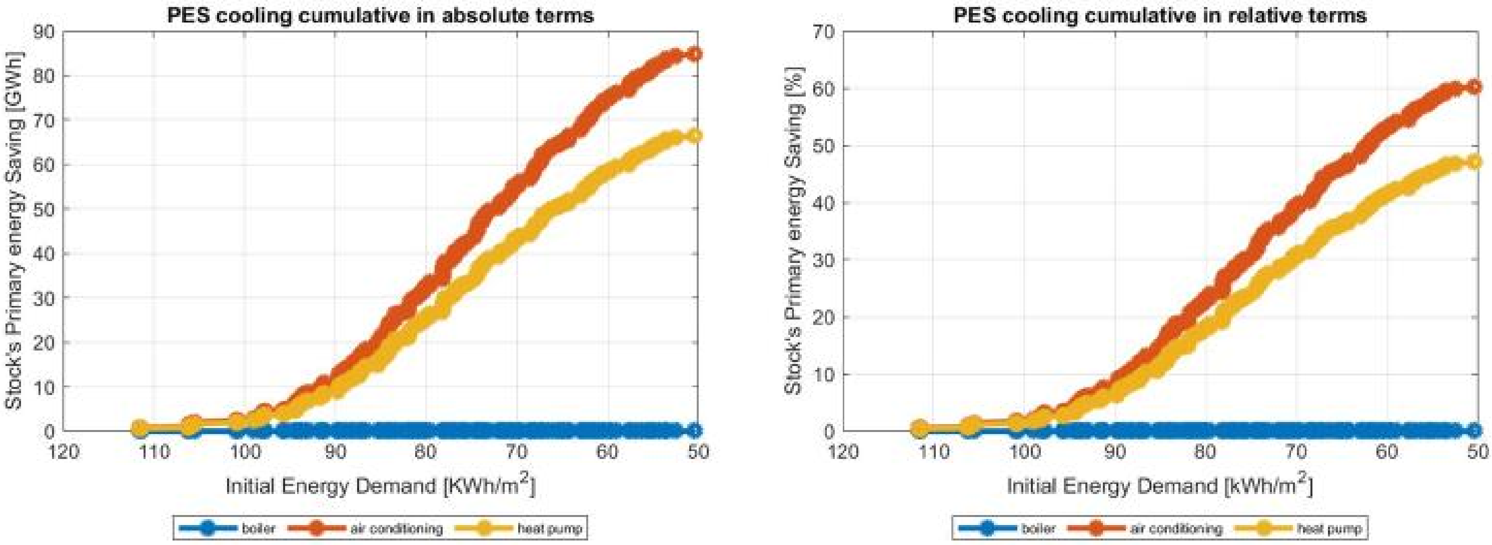


Figure 69 SYSTEM REPLACEMENT: PES INDICATOR, COOLING SHARE. On the right, the indicator in relative value; on the left the indicator in absolute value.

Focusing on the heating share, results are shown in Figure 70. The maximum PES is reached with the heat pump system. Indeed, by applying this solution to all the stock a PES of almost 1000GWh is reached accounting for roughly 70% of the total 's ED, whereas the relative PES reached with the boiler replacement account for roughly 20%. This behaviour is due to the fact that the thermal efficiency of 0.92 is about 20% higher than the average efficiency of the existent system. In contrast, the COP of the heat pump is about 70% higher than the equivalent average COP of the existent system (thermal efficiency/national electric efficiency).

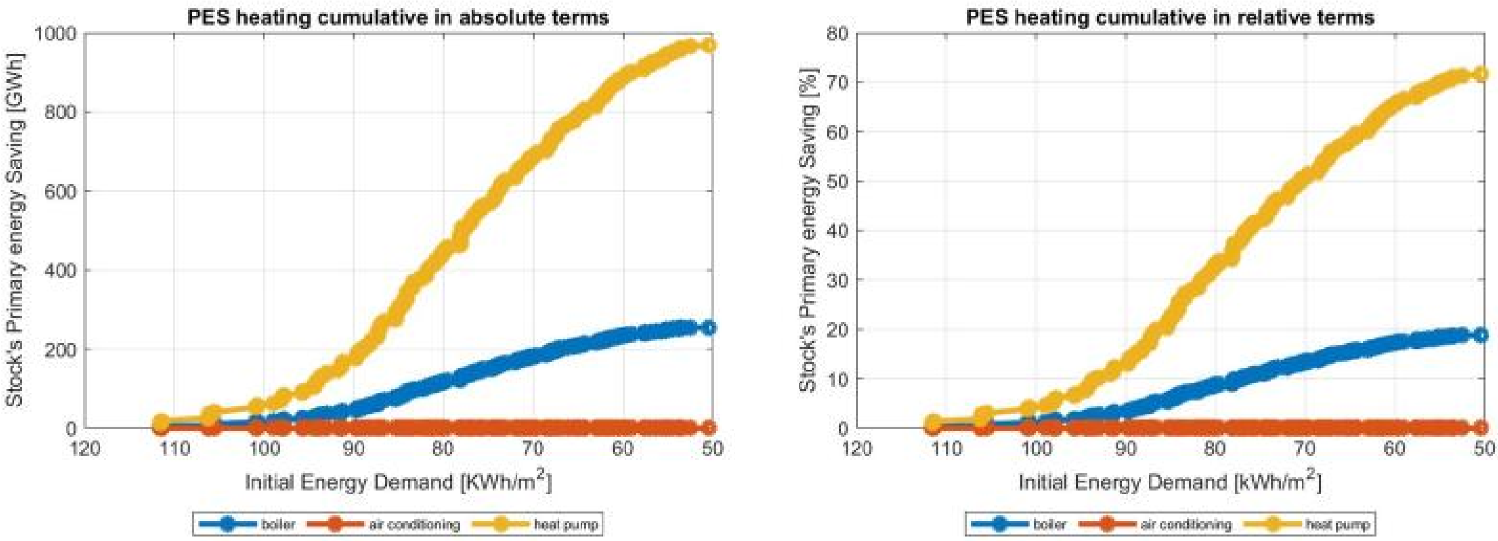


Figure 70 SYSTEM REPLACEMENT: PES INDICATOR, HEATING SHARE. On the right, the indicator in relative value; on the left the indicator in absolute value.

Finally, the results about the total share, showed in Figure 61, confirm the heat pump as the best system and reveal the possibility of reducing 70% of the stock's energy demand only with its replacement.

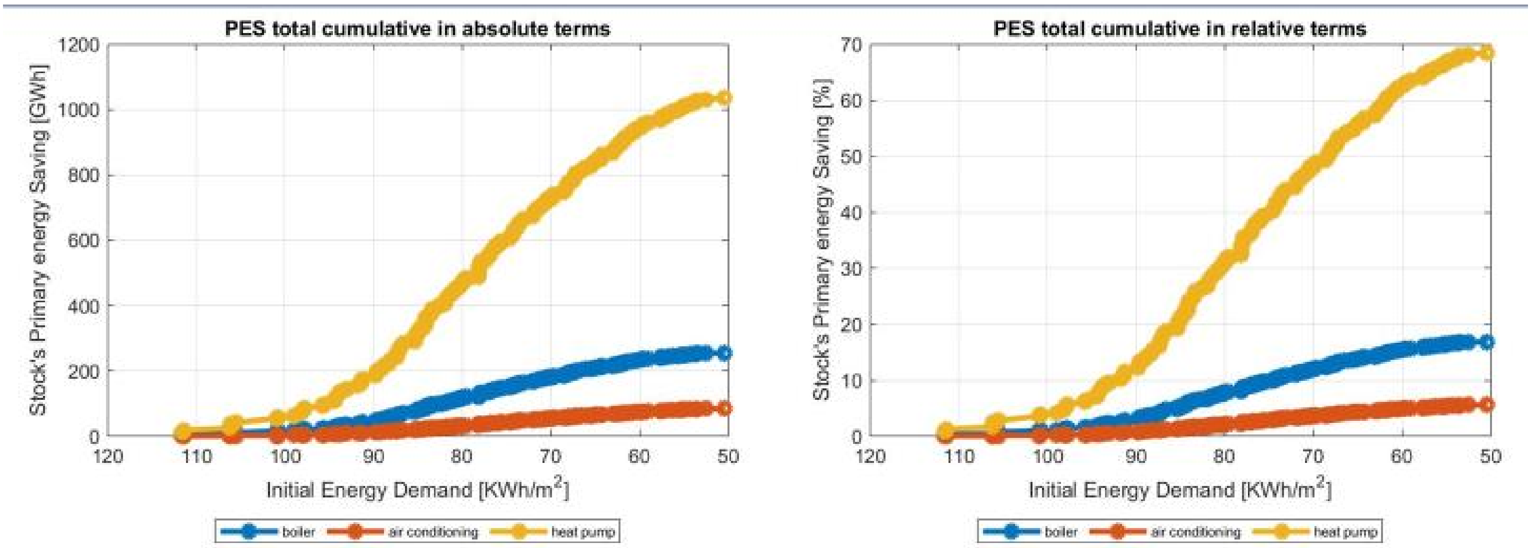


Figure 71 SYSTEM REPLACEMENT: PES INDICATOR, TOTAL SHARE. On the right, the indicator in relative value; on the left the indicator in absolute value.

Concerning the Carbon Energy Saving, results are reported in Figure 72, Figure 73 and Figure 74 and account respectively for the cooling, heating and total share. The relatives' values of the total share differ from the ones in Figure 71 because the PES obtained during the cooling produce a greater CES due to the electricity saving. Indeed, the CES obtained with deep insulation accounts for 70% of the total CO_2 produced. Therefore, by installing the heat pump in all the buildings of the stock, it is possible to reach the "decarbonized stock" 2050 European target.

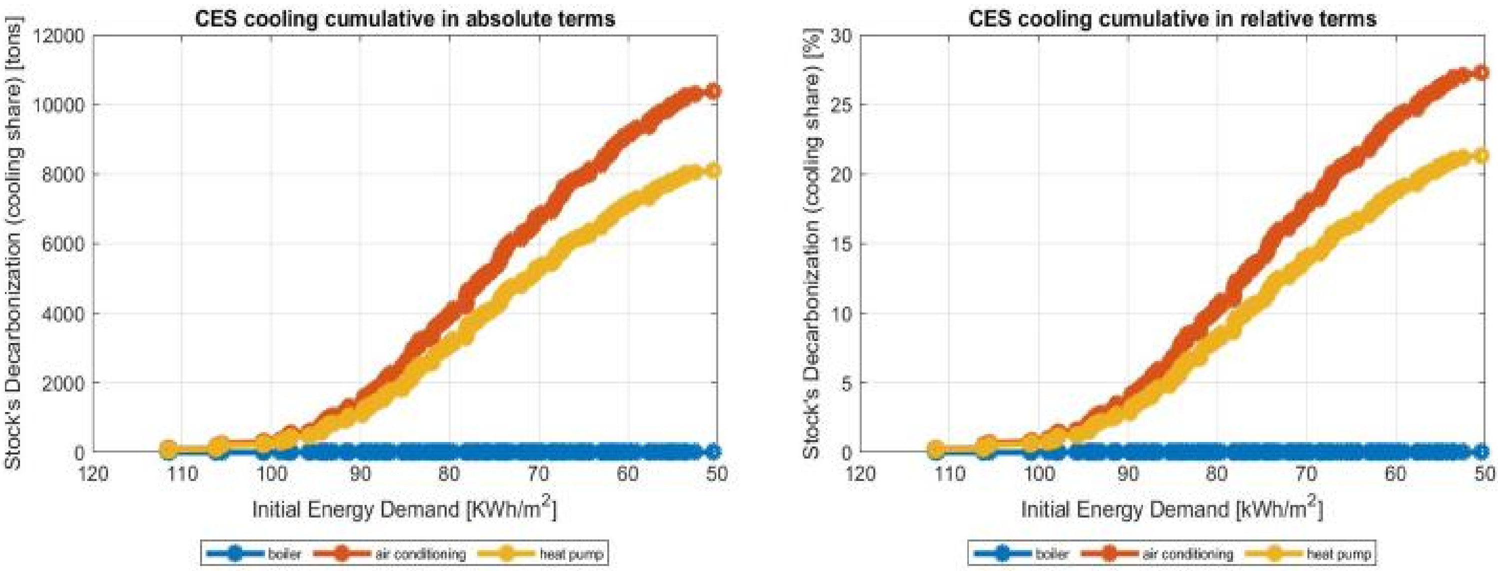


Figure 72 SYSTEM REPLACEMENT: CES INDICATOR, COOLING SHARE. On the right the indicator in relative value; on the left the indicator in absolute value.

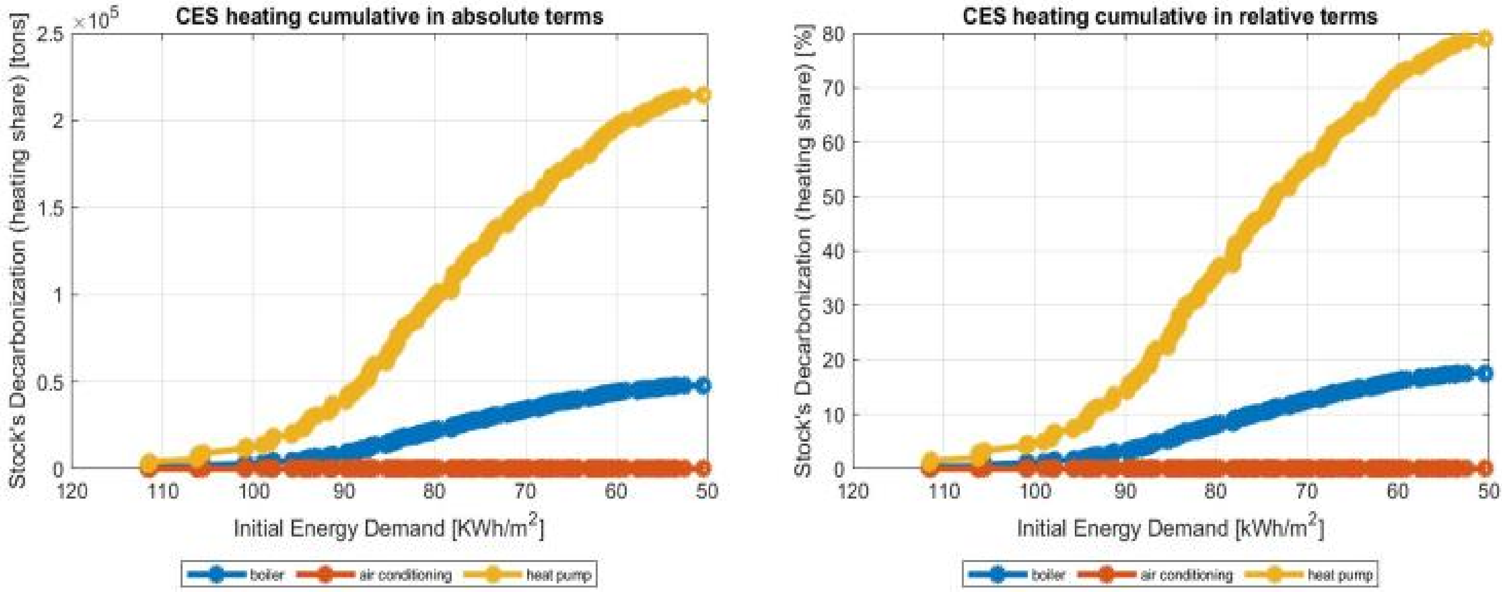


Figure 73 SYSTEM REPLACEMENT: CES INDICATOR, HEATING SHARE. On the right the indicator in relative value; on the left the indicator in absolute value.

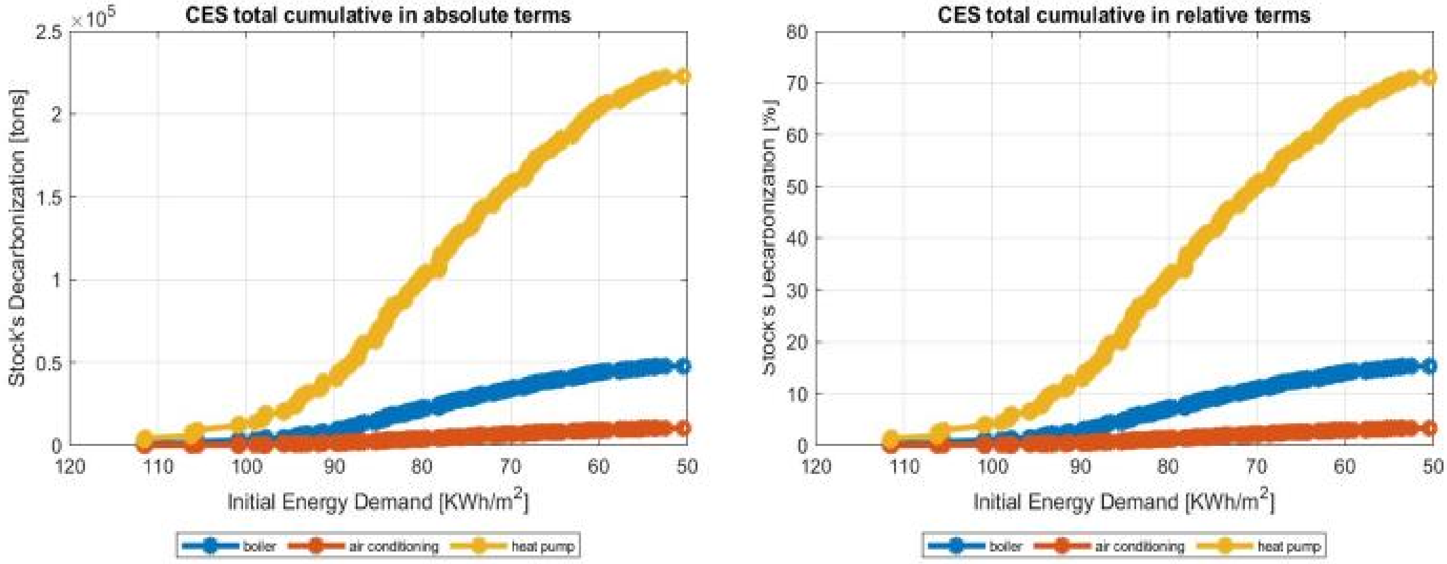


Figure 74 SYSTEM REPLACEMENT: CES INDICATOR, TOTAL SHARE. On the right, the indicator in relative value; on the left the indicator in absolute value.

The last indicator evaluated within the technical analysis framework is the Power Peak Saving in MW. Differently from PES and the CES, results of the PPS are divided only for the cooling and heating since the sum of the two shares is not of interest because the power is both of different entity (thermal and electric) and happens in different periods of the year.

Regarding the Cooling share, results are shown in Figure 75. As system affects the ideal demand in a linear way, the trend remains equal to those observed for PES and CES. Specifically, the PPS produced by the Airconditioning accounts for 27%, whereas that produced by the heat pump is equal to 23%.

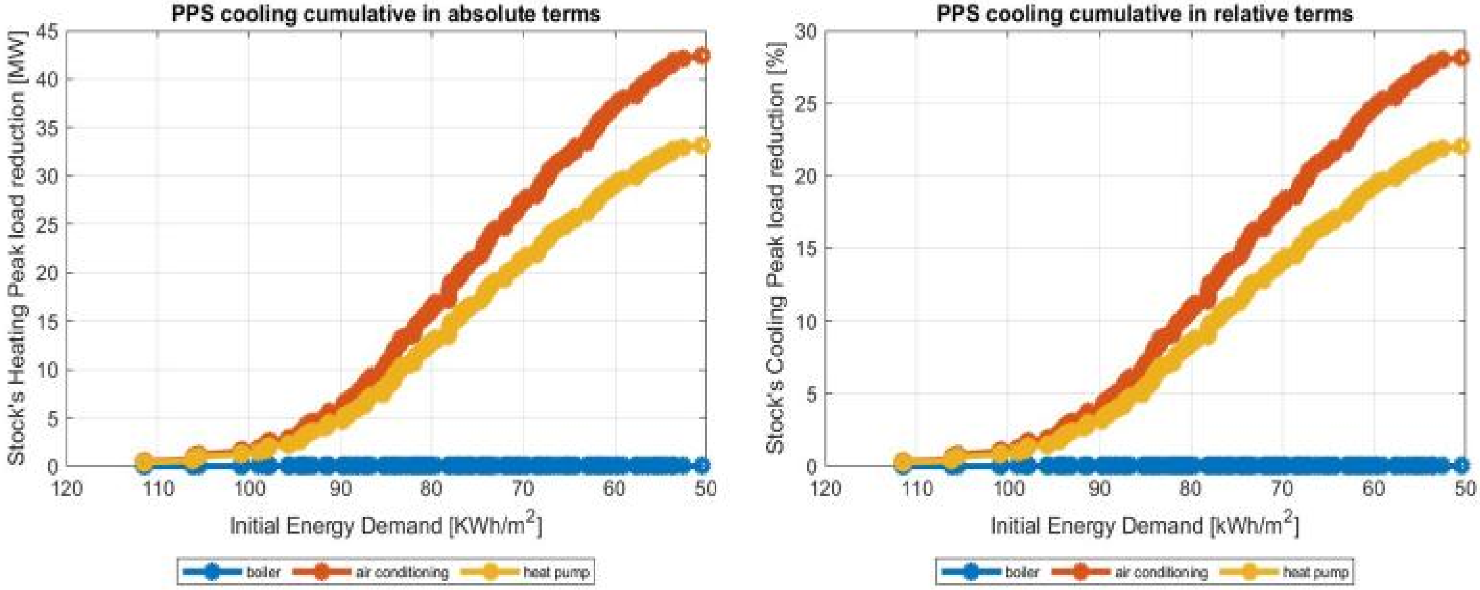


Figure 75 SYSTEM REPLACEMENT: PPS INDICATOR, COOLING SHARE. On the right, the indicator in relative value; on the left the indicator in absolute value.

Focusing on the heating share, results are shown in Figure 66. In analogy with the cooling PPS, the trends remain equal to those observed for PES and CES. Specifically, the PPS produced by the boiler accounts for 80%, whereas that produced by the heat pump is equal to 20%.

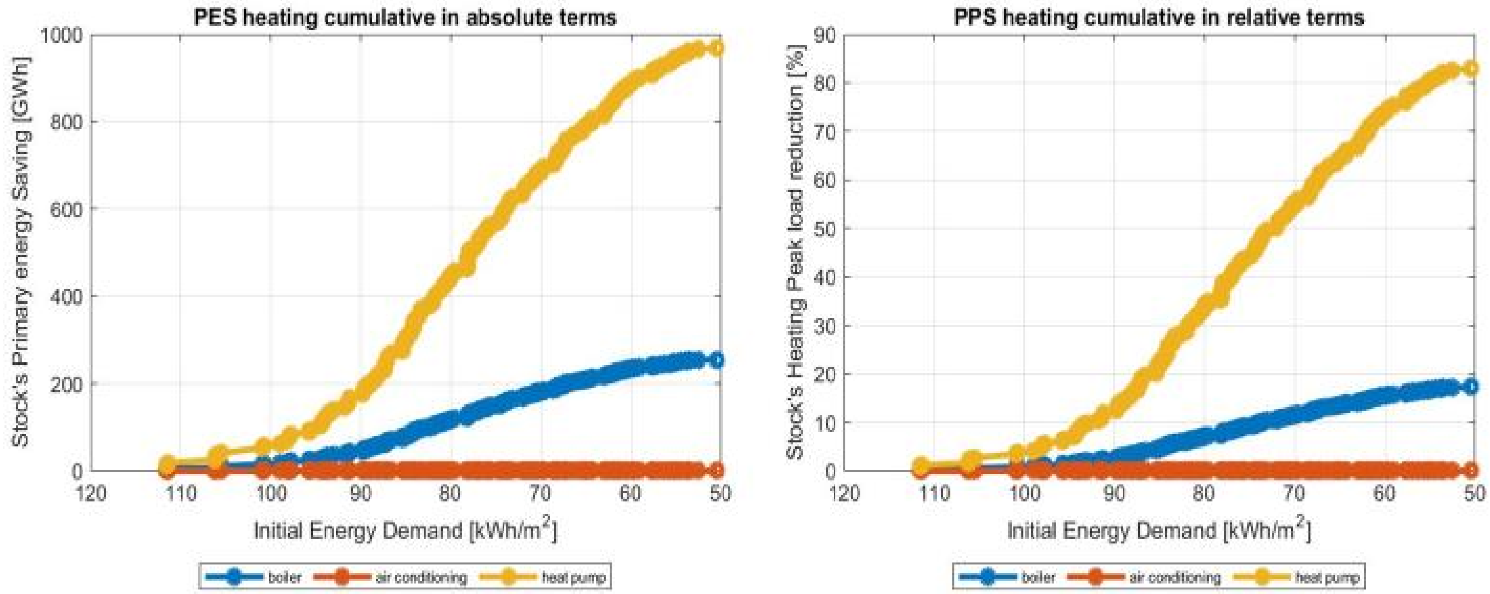


Figure 76 SYSTEM REPLACEMENT: PPS INDICATOR, HEATING SHARE. On the right, the indicator in relative value; on the left the indicator in absolute value.

Concerning the Economic analysis, Figure 77 illustrates the results regarding the NPV and PBT indicators. The heat pump, thanks to the remarkable performances abovementioned and the fact that the technology can be used both for cooling and heating, determines the higher NPV for a value of 1300Million of euro. According to the positive NPV results, all the PBT are lower than about 15 years, with the lowest PBT equal to 6 years obtained with the boiler.

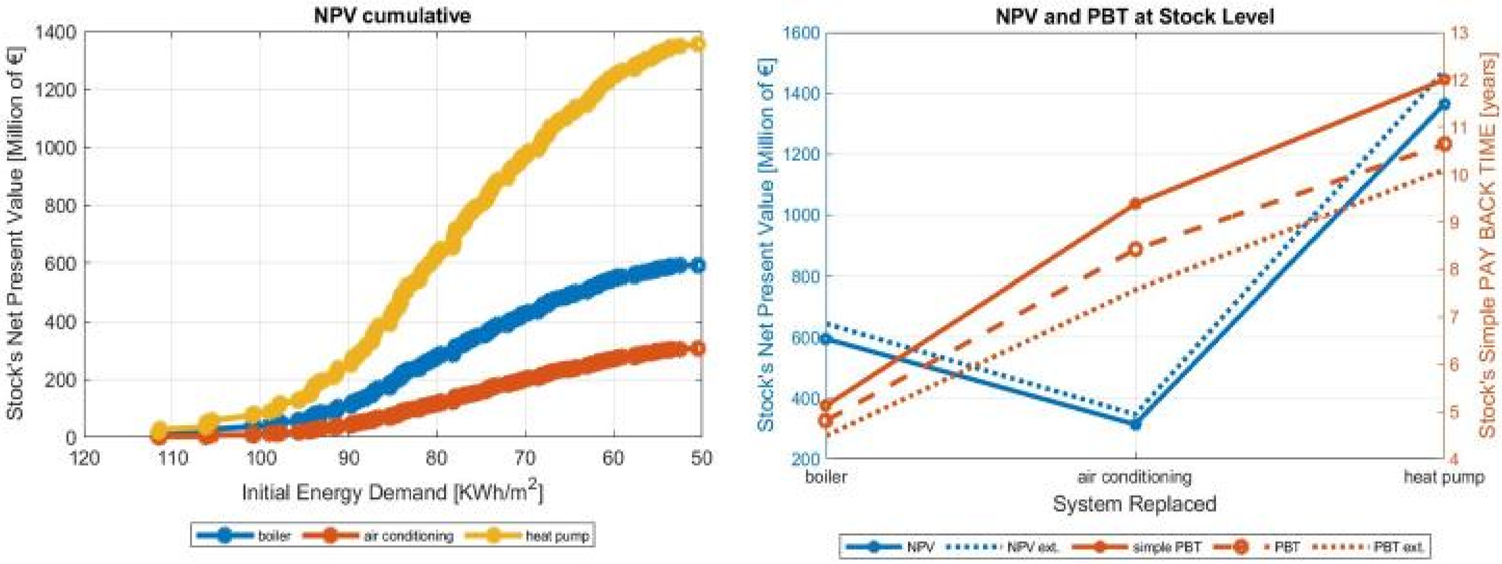


Figure 77 SYSTEM REPLACEMENT: NPV and PBT. On the left the cumulate of the NPV without considering the externality. On the right the result obtained when the measure is applied on all the stock: in blue, the NPV with and without considering the externality; in orange the simple PBT, the PBT and the PBT considering the externality.

Figure 78 shows results related to the CI_{PBT10} and the Incentives. As the PBT for the boiler and the air conditioning system is lower than 10 years, they do not require any investment from the government to ensure a PBT of 10 years. Instead, the heat pump does not require incentives only for buildings with an initial energy demand lower than 80 kW/m^2. This behaviour is due to the fact that the PBT required for buildings with an initial energy demand lower than 80 kW/m^2 is greater than ten years. Regarding the investment cost, the minimum difference between the CI and the CI_{PBT10} is registered for the air conditioning system and accounts for 7 €/m².

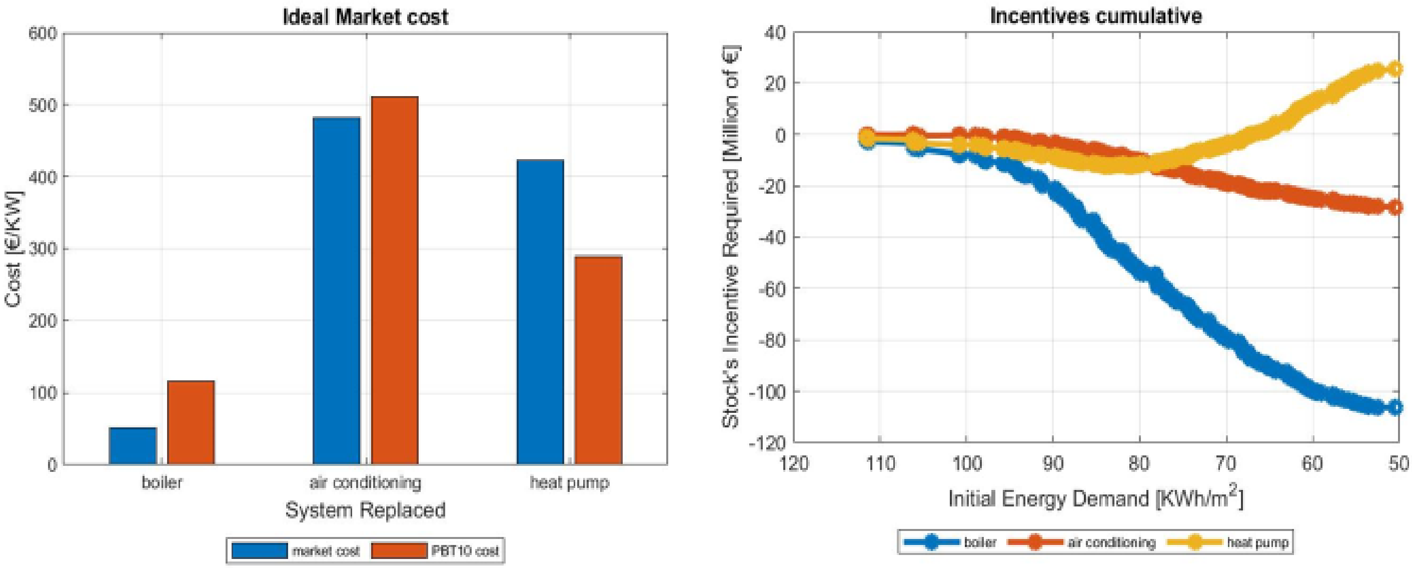


Figure 78 SYSTEM REPLACEMENT: CI_{PBT10} and INCENTIVES. On the left the comparison between the CI and CI_{PBT10} for the different configuration of windows. On the right, the cumulative of the Incentives indicator.

3.5 Discussion of the Results

In this section results of the economic and technological analysis are synthesized by comparing the PES and the Incentives in the case that all the considered stock is retrofitted. In this way, through this graph, the legislator will have a first answer to the question "How much Investment do I need to support the exploitation of these technologies on stock level and what will be the result?".

3.5.1 Window

Overall result of the retrofit analysis is reported in Figure 79. In this figure the most important result of the economic and technological analysis is synthesized by comparing the PES and the Incentives in the case that all the considered stock is retrofitted. In this way, through this graph, the legislator will have a first answer to the question "How much Investment do I need to support the exploitation of these technologies on stock level and what will be the result?". From the graph Results it is clear that among the five technologies analysed the window characterized by a transmittance of 1.1W/m²K and a solar factor of 0.609 achieve the best economic and technological performances as it maximizes the PES, reducing the Primary energy demand of

56 GWh, and minimize the incentives required up to 80 million of € to ensure a PBT of 10 years across all the buildings of the stock.

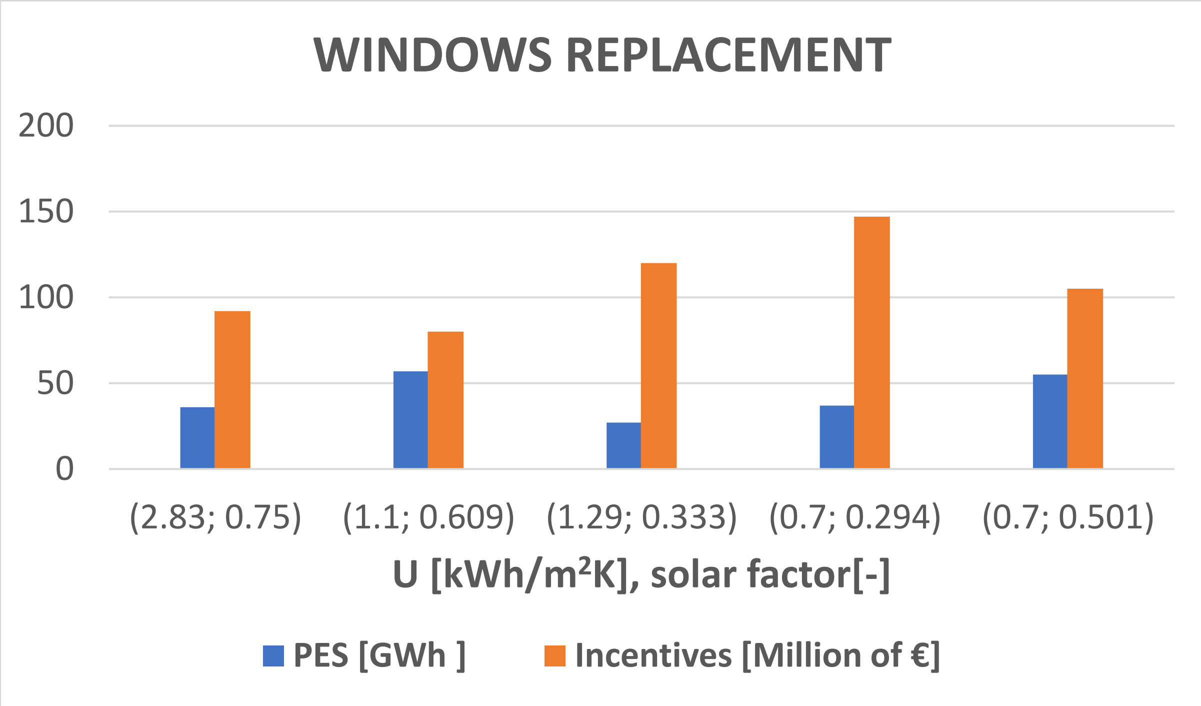


Figure 79: WINDOWS REPLACEMENT: Comparison between PES and Incentives when all the archetypes are retrofitted, considering the five different technology of windows.

3.5.2 Roof insulation

Figure 80 reports the final result of the retrofit analysis and clearly shows that the PES produced start to decrease the slope for thickness greater than 15 cm, whereas the Incentives required becoming to have a linear trend as the PES does not significantly variate. Therefore, it can be concluded that the thickness of the roof insulation should not go over the 15cm as the investment is not repaid by a similar growth of energy saving. In details, by applying an insulation layer of 7-15 cm, a PES in the order of 180-200 GWh will be produced and it will demand of incentives between 75-80 million €.

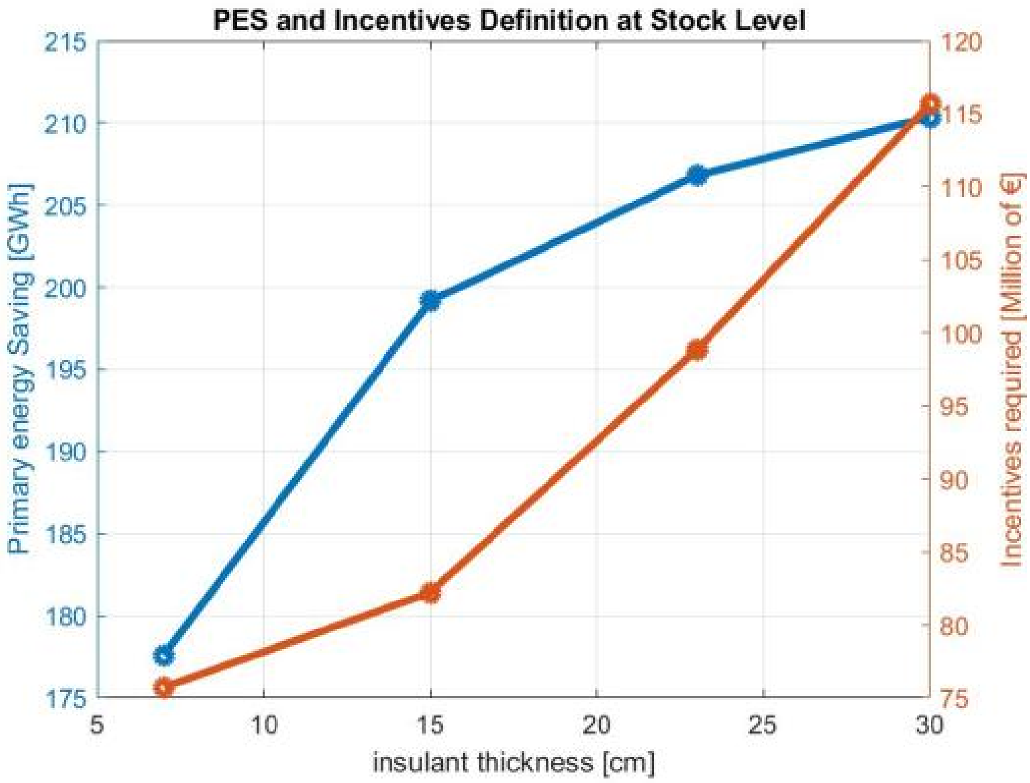


Figure 80 ROOF INSULATION: Comparison between PES and Incentives when all the archetypes are retrofitted, considering the five different technology of Insulation Thickness.

3.5.3 External Wall insulation

The final results of the retrofit analysis are reported in Figure 81 which shows a linear trend of the investment required whatever the insulation thickness because the increasing of the Investment cost with the insulation is dominant respect to the Economic benefit produced by the energy saving. For this reason, it can be said that even if the saturation in the PES starts from insulation thickness greater than 10cm, the consistent growth of the required incentives made the 5cm solution the most convenient, accounting for a PES of 480 GWh and 800 million Euros of required incentives.

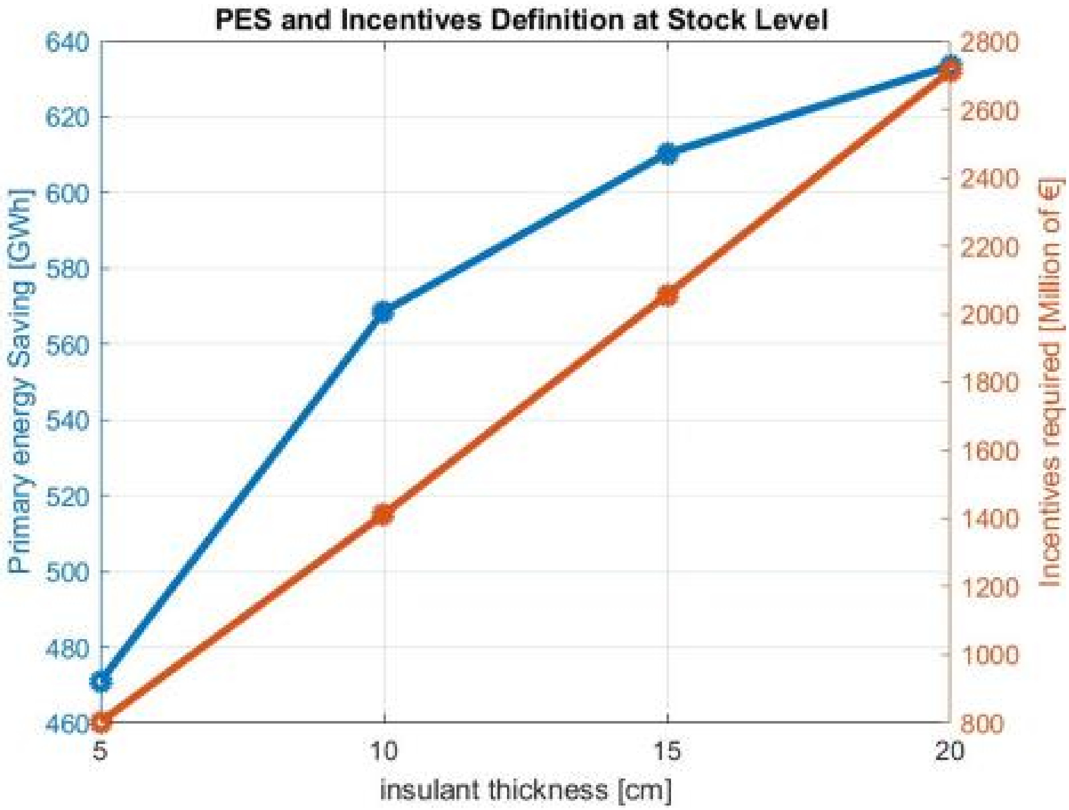


Figure 81 EXTERNAL WALL INSULATION: Comparison between PES and Incentives when all the archetypes are retrofitted, considering the five different thickness of insulation.

3.5.4 Internal Wall insulation

The final result of the retrofit analysis is reported in Figure 82. In analogy with Figure 81, the graph shows a linear trend for the investment required whatever the insulation thickness because the increasing of the Investment cost with the insulation is dominant respect to the Economic benefit produced by the energy saving. Therefore, although the saturation in the PES starts from an insulation thickness greater than 15cm, the consistent growth of the required incentives made the 7cm solution the most convenient, accounting for a PES of 500 GWh and 200 million of required incentives.

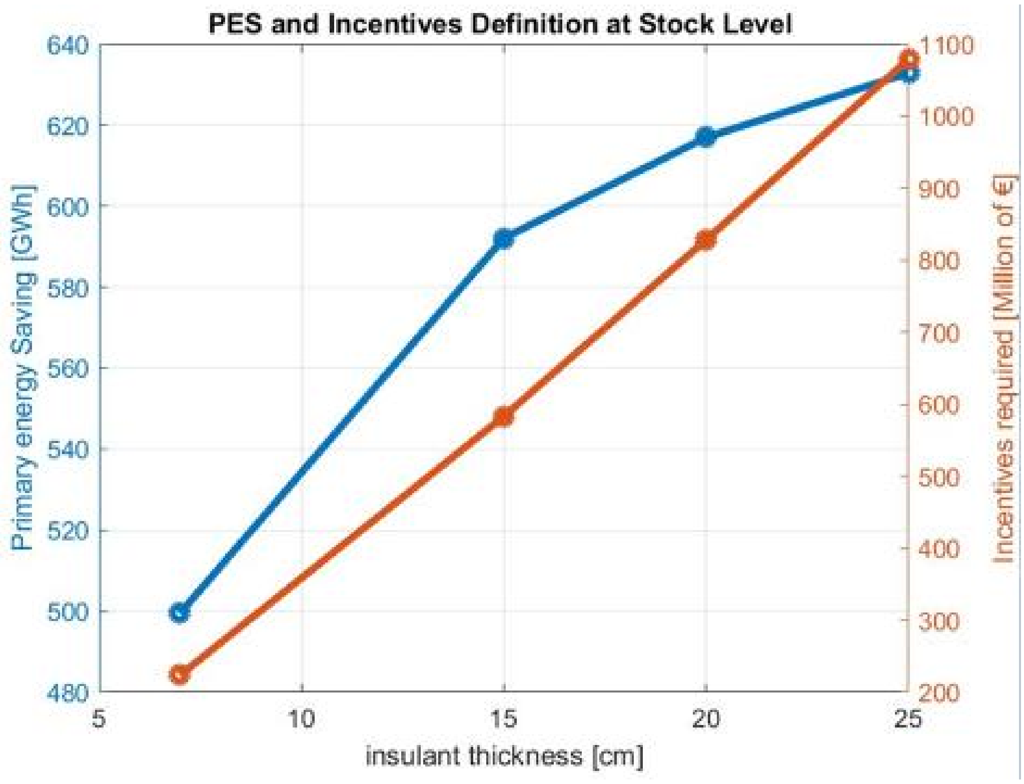


Figure 82 INTERNAL WALL INSULATION: Comparison between PES and Incentives when all the archetypes are retrofitted, considering the five different Insulation Thickness.

3.5.5 System replacement

The final result of the retrofit analysis is reported Figure 83. In the figure it is remarked again that the PBT lower than 10 achieved by the Boiler and the Air conditioning system produce a negative demand for the incentives, by means that they are not necessary. On the other hand, according to the trend seen in Figure 78, the PBT achieved by the heat pump is lower than 10 years only for the buildings with an initial energy demand greater than 80 kWh/m^2. For this reason, when all the stock is retrofitted, a presence of incentives is required to ensure a PBT of 10 years for all the buildings of the stock. Accounting, for the energy saving the best performances are reached by the heat pump for a value of 1000 GWh thanks to the high value of COP (around 70 higher than an equivalent COP of the existing boiler). Therefore, as a conclusion, if the Boiler and air conditioning replacement do not require the incentives from the government, the installation of the heat pump has to be supported with 250 million of € but will produce PES up to 4-5 times higher than the other two systems.

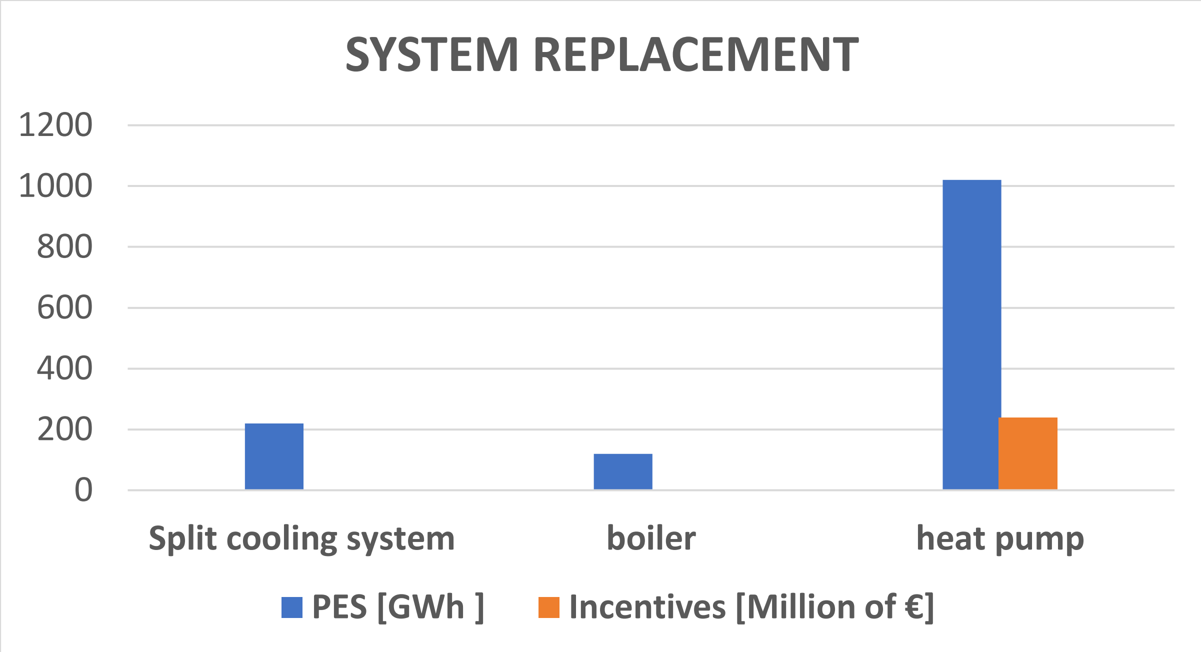


Figure 83 SYSTEM REPLACEMENT: Comparison between PES and Incentives when all the archetypes are retrofitted, considering the five different technology of systems.

3.5.6 Best solution

The best retrofit solution among those analysed appears to be the installation of an efficient heat pump. Indeed, it achieves:

- **Lowest incentives:** Incentive to ensure a Payback time of 10 years are required only for buildings with an energy demand lower than 80 kWh/m^2; therefore, 20 Million Euros are enough to allow its installation in all the buildings of the stock, ensuring a PBT lower than 10 years for all the privates.
- **Highest PES**: Thanks to the fact that the heat pump with high COP value (greater than 2) performs better than efficient boilers (efficiency of 0.9), the installation of the heat pump produces up to 1000 GWh of Primary energy savings.
- **Electrification of the building**: Choosing the heat pump over the boiler allows the decarbonization of the stock, focusing the problem only on the production system.

For these reasons, to conclude the analysis in Figure 84 and Figure 85 it is reported how the energy demand profile of the stock will change during heating and cooling demand if the heat pump would be applied on all the buildings of the stock.

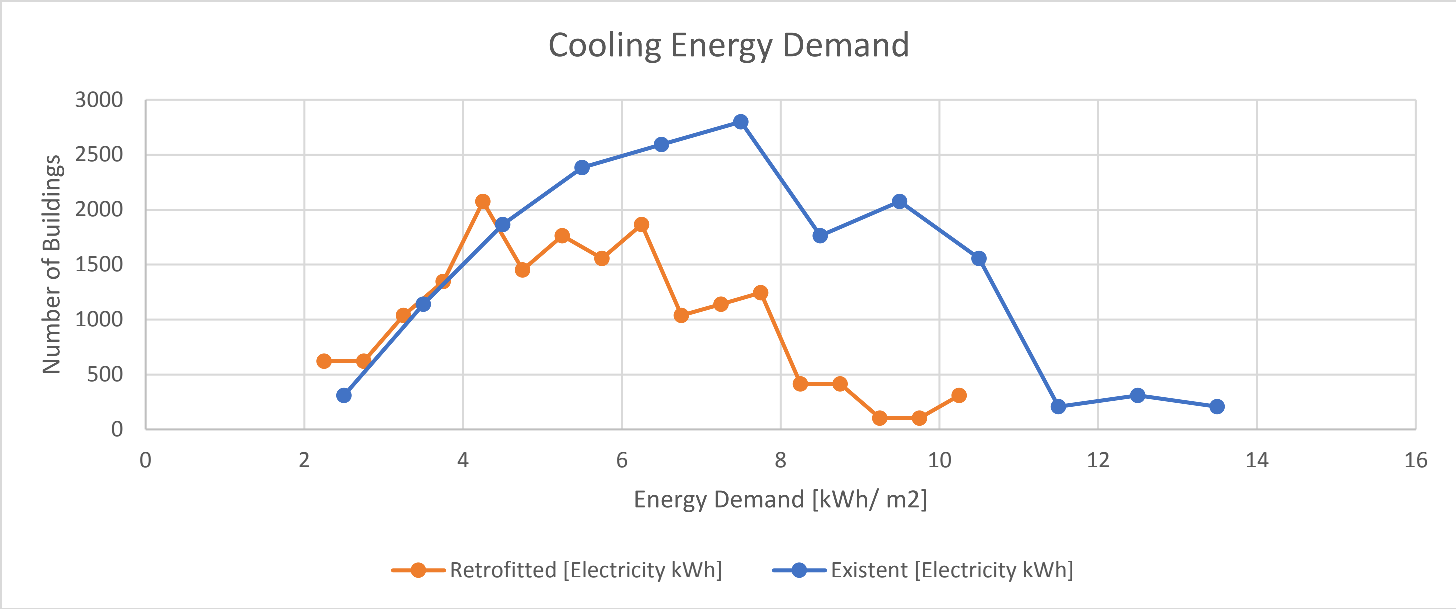


Figure 84 Comparison of the Existing cooling profile and the cooling profile achieved if the heat pump proposed is installed on all the building of the stock.

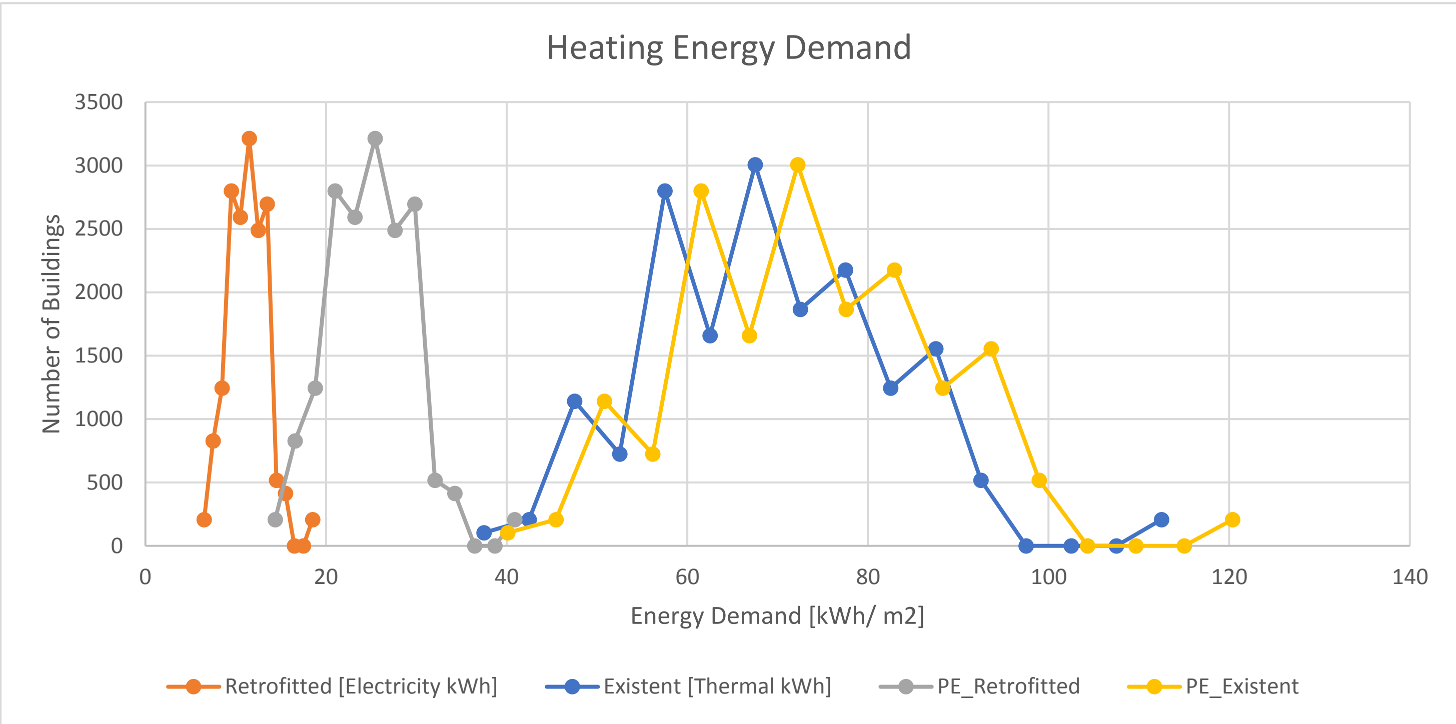


Figure 85 Comparison of the Existing cooling profile and the cooling profile achieved if the heat pump proposed is installed on all the building of the stock.

4 CONCLUSION

A multi-stage methodology has been developed in order to evaluate the implementation of the energy actions for the retrofitting of the buildings. This refers to the buildings belonging to the same category with an aim of defining an economically convenient path that leads the city toward the stock decarbonization goals introduced by the European directives. In details, the effect of these energy actions are investigated in economic terms, through NPV consideration, and in technological terms studying the indicators PES (reduction of the primary energy), CES (Reduction of the CO_2 emissions) and PPS (reductions of the stock's peak power requirement) in order to achieve two main objectives:

- To quantify the incentives that are necessary to produce an affordable PayBackTime(PBT).
- To show how the global effect of the applied solution changes by modifying the number of retrofitted buildings

The methodology is based on uncertainty and sensitivity analyses carried out via the coupling Energyplus and MATLAB®. The main originality of this novel methodology is:

1 Development of a method that directly produces the surrogate model with the minimum number of Archetypes of the Existent building stock.

2 Development of a method that allows the user to relate the number of archetypes with the final accuracy of the surrogate model.

3 Basing the retrofit on the Existent Building stock instead of creating an "ex-Novo" stock: the archetypes of the surrogate model (previously created) are directly retrofitted starting from the less efficient ones and proceeding forward until the retrofit is convenient. In this way, because there will be a direct correspondence between the archetype of the Inefficient and Retrofitted stock, the methodology can record the results of the measure also at the buildings' level.

Therefore, an archetype bottom-up approach is adopted in stock modelling. It permits to enhance the quality of data through statistical consideration when only limited information of the stock is available. The approach consists of two main stages: the building stock creation and the retrofit of the stock. The *building stock creation* is further divided into:

- **Data collection:** First, the building category is defined in terms of end-use (Residential or Commercial), number of buildings and construction year. Secondly, buildings information is collected using both TABULA and local database in order to identify (i) the variables that will be used to define a generic Archetype, (ii) the variables' variation range and (iii) which discrete values can be assumed by the variables. Finally, the Average Archetype of the category is defined.

- **Sensitivity analysis:** The variables of the average archetype model are varied one by one within their specified range. Thus, dominant input variables are identified by recording the variation obtained in the output.
- **Archetype Production:** A probability distribution is associated with each dominant input variable. Then, other archetypes beyond the average one are created by combining the discrete values of these variables statistically.
- **Model size definition:** Each time a new archetype is created, the error related to the changes in the output results is evaluated. Therefore, when the addition of a new archetype to the model produces an error minor than the threshold assumed, the minimum size is reached.

Concerning the *Stock retrofit*, the methodology can be exploited through both parametric and multi-objective analysis. In detail, the energy solution is analysed by two categories of indicators:

- *Economic Indicators*: aim to quantify the economic benefit generated by the retrofit solution and define the incentives required to ensure a PBT of years for the private investors.
- *Technological Indicators*: aim to quantify the solution's efficiency in terms of energy demand, power demand and CO_2 savings.

Finally, each of the indicators is reported on a characteristic graph, which is able to give information about:

- the cumulative impact of the retrofit measure with a retrofitted fraction of the stock discretely variating from 0 (none of the archetypes retrofitted) to 1 (all the stock retrofitted)
- The effect of the measure of each singular building.

In this way, the policymaker is able to define what is energy efficiency measure that reaches the optimum between the economic and technological effect, on which portion of the stock it should be applied, and what will be the incentives required.

As a case study, the methodology is applied to a specific residential building category of the city of Barcelona, accounting for the buildings built between 60' and 79' for a total of 17209 buildings. The result is a surrogate model in which the minimum number of archetypes that ensure an error below the threshold of 3% is equal to 169. Concerning the retrofit moment, the energy solutions proposed regard windows, roof and wall insulation, and system replacement and the results implying the following conclusion for the examined stock:

- ***Window***

Among the five technologies analysed, the window characterized by the transmittance of 1.1W/m^{2}K and the solar factor of 0.609 achieves the best economic and technological performances as it maximizes the PES, reducing the Primary energy demand of 56 GWh, and minimizes the incentives required up to 80 million of € to ensure a PBT of 10 years across all the buildings of the stock.

- ***Roof insulation***

It can be concluded that the thickness of the roof insulation should not go over 15cm as the investment is not repaid by a similar growth of energy saving. In details, by applying an insulation layer of 7-15 cm, a PES in the order of 180-200 GWh will be produced and it will demand incentives between 75-80 million €.

- ***External wall insulation***

The high investment cost made the 5cm solution the most convenient, accounting for a PES of 480 GWh and 800 million Euros of required incentives.

- ***Internal wall insulation***

As happened with the external wall insulation, the high investment cost made the 7cm solution the most convenient, accounting for a PES of 500 GWh and 200 million of required incentives.

- ***System replacement***

The installation of a high efficiency heat pump, although it produces higher payback time with respect to the air conditioning and boiler solution, it produces a significant PES of 1000GWh and 250 million of Euro of the incentives.

Therefore, as a general conclusion of the retrofit options, it can be said that for the presented case study the optimal measure is the introduction of a high efficiency heat pump. Indeed, the target set by the EBPD of a decarbonized stock can be directly reached and the incentives required are in the order of 20 million €. Moreover, the electrification of the production system will leave further improvement margin as the CO2 emissions will be additionally decreased with higher renewable penetration in the energy mix of the city, that can be expected in the future.

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6 ANNEX

6.1 Distribution of the significant variables

In order to understand the difference between the surrogate model and the complete model, in the following figures the distributions of the significant variables across the stock can be seen, comparing the Surrogate and the complete model.

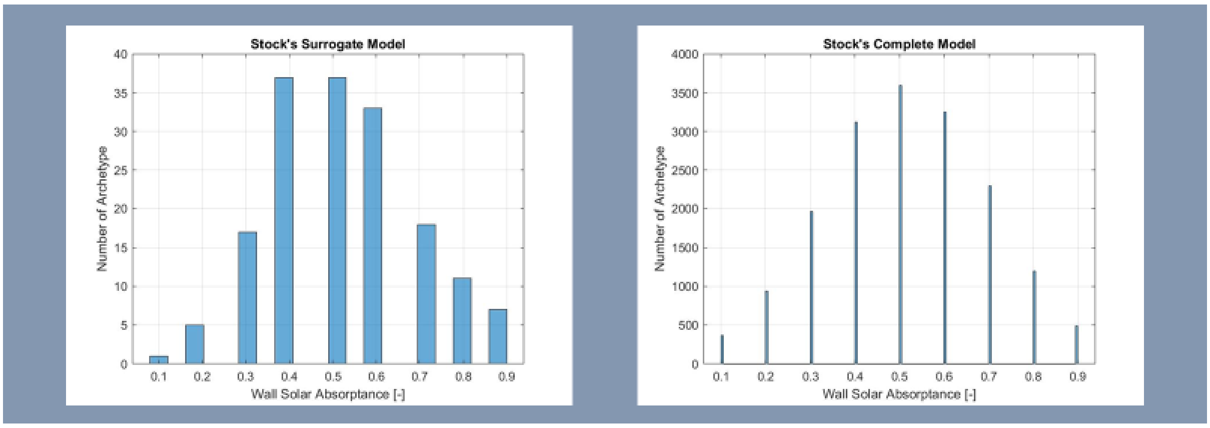

Figure 86 :Distribution of the Wall Solar Absorptance. On the left, the variable distribution in case of the entire Building stock; on the right, the variable distribution across the surrogate model

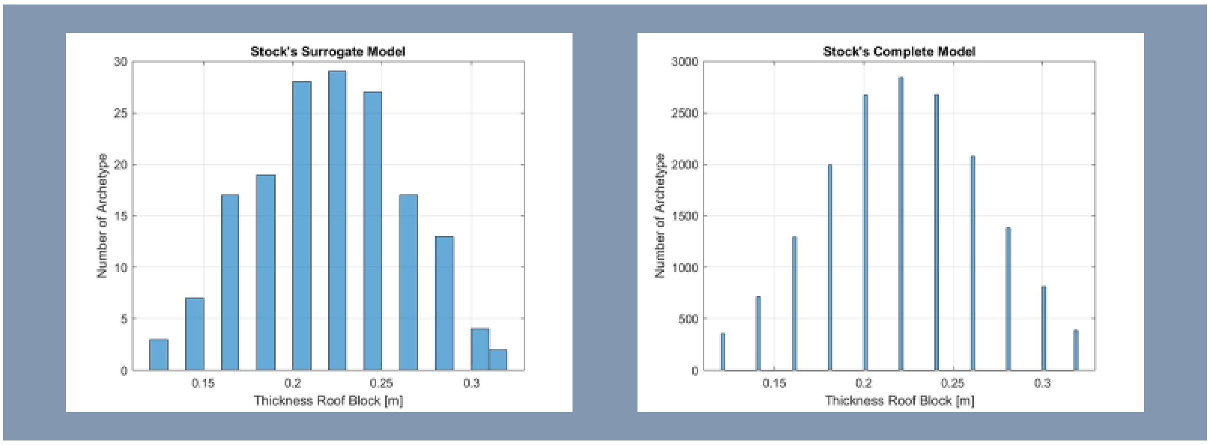

Figure 87:Thickness Roof Block. On the left, the variable distribution in case of the entire Building stock; on the right, the variable distribution across the surrogate model

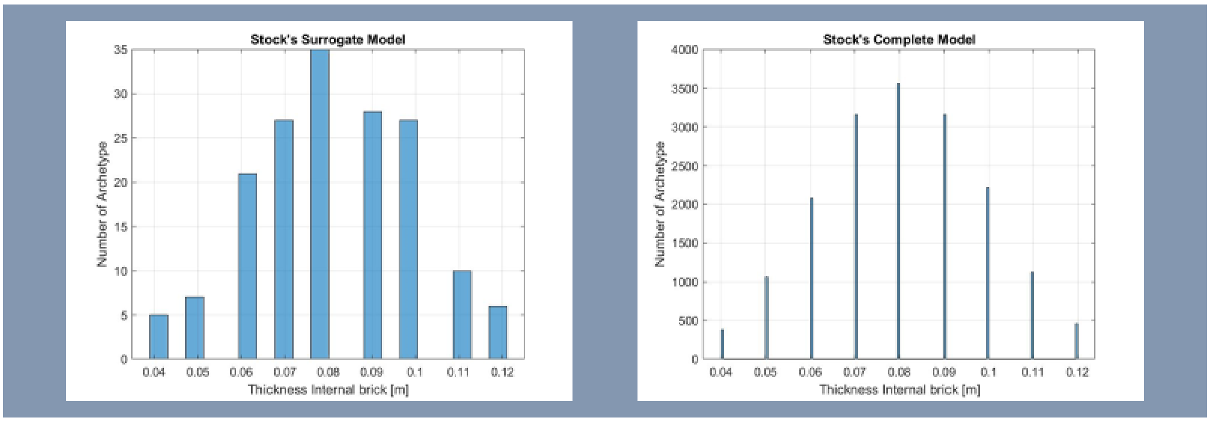

Figure 88:Distribution of the Thickness Internal brick. On the left, the variable distribution in case of the entire Building stock; on the right, the variable distribution across the surrogate model

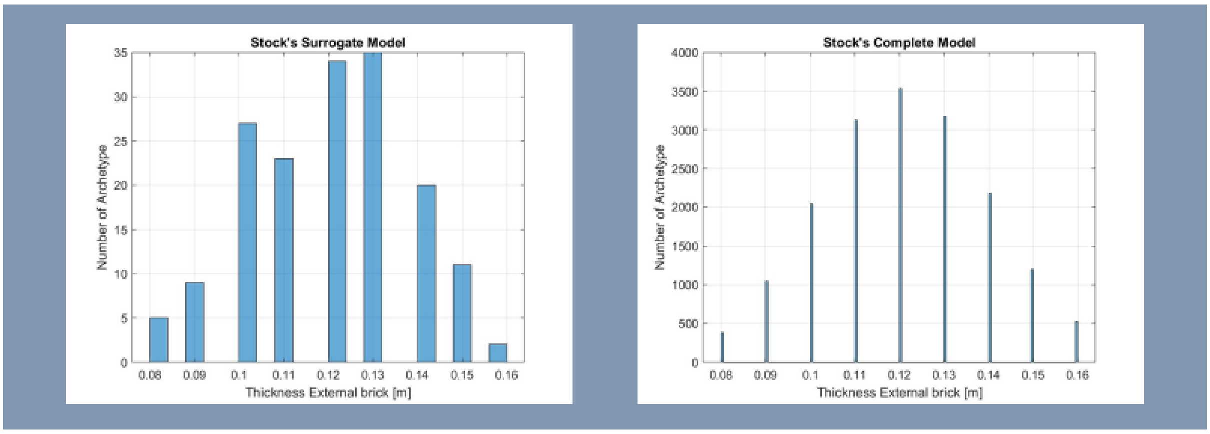

Figure 89:Distribution of the Thickness External brick. On the left, the variable distribution in case of the entire Building stock; on the right, the variable distribution across the surrogate model

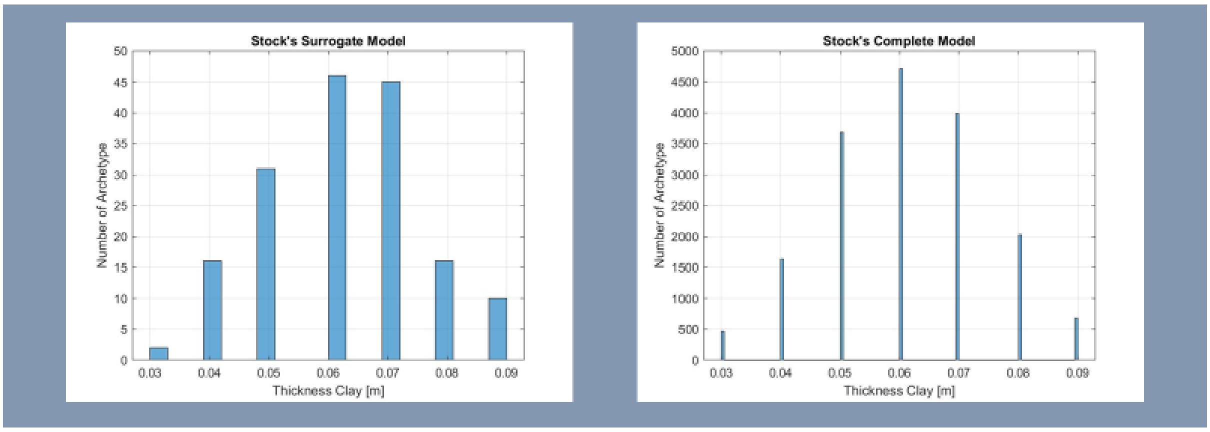

Figure 90:Distribution of the Thickness Clay. On the left, the variable distribution in case of the entire Building stock; on the right, the variable distribution across the surrogate model.

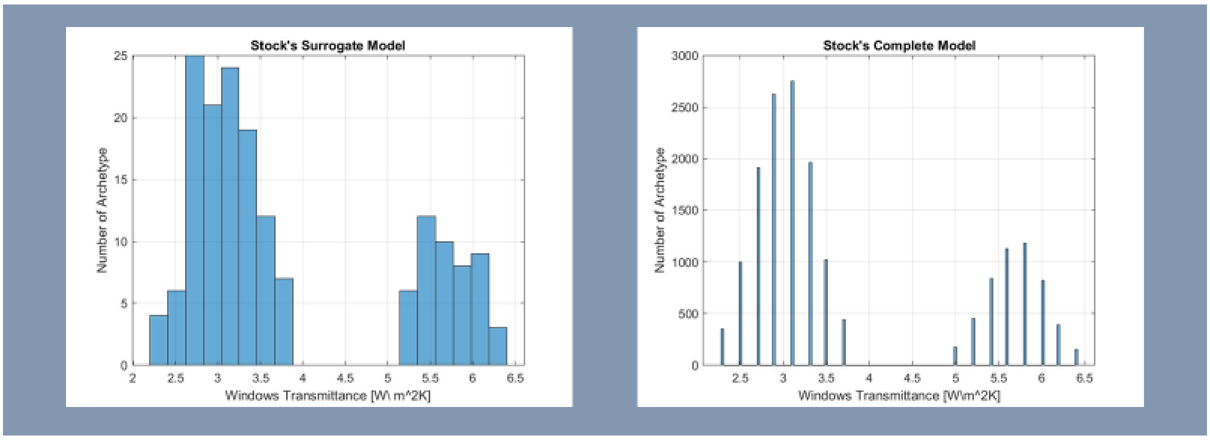

Figure 91:Distribution of the Windows Transmittance. On the left, the variable distribution in case of the entire Building stock; on the right, the variable distribution across the surrogate model

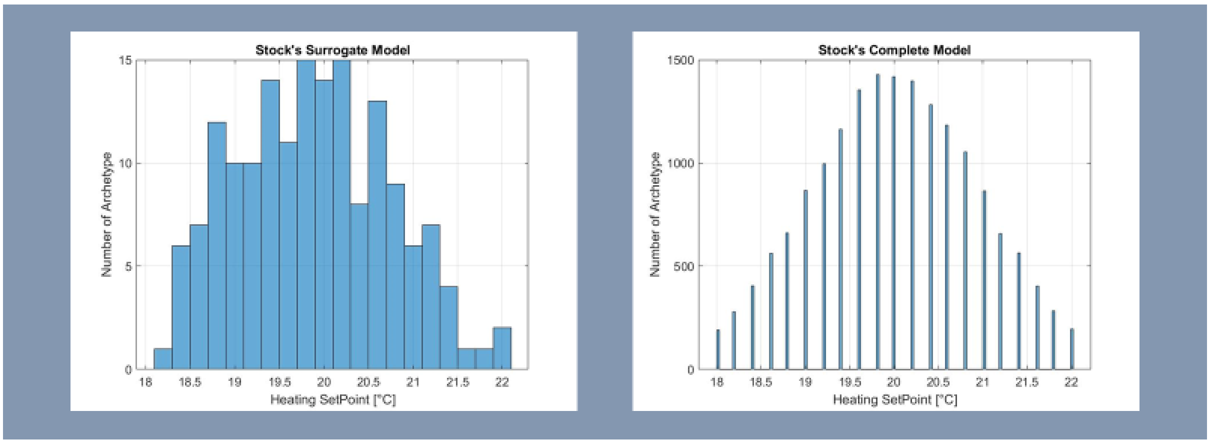

Figure 92:Distribution of the Heating Set Point. On the left, the variable distribution in case of the entire Building stock; on the right, the variable distribution across the surrogate model.

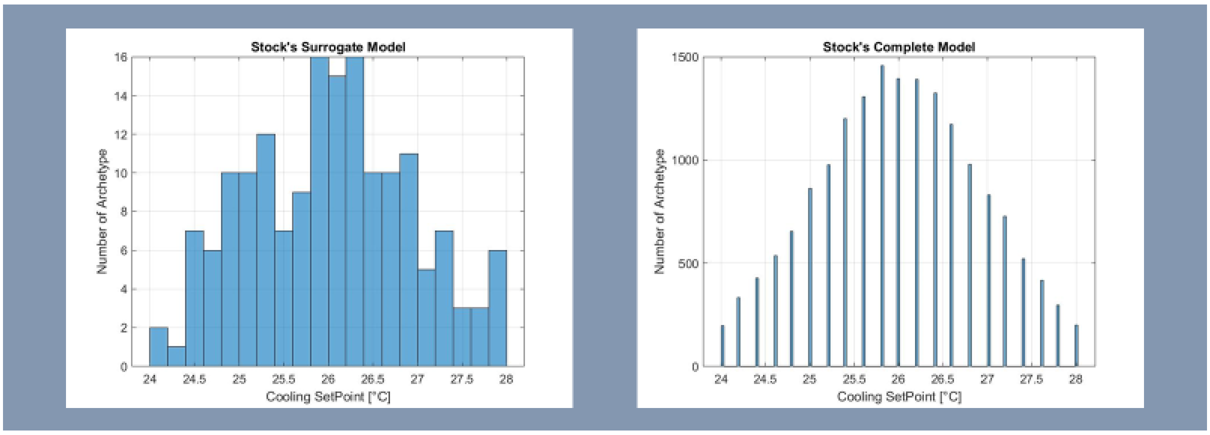

Figure 93:Distribution of the Cooling Set Point. On the left, the variable distribution in case of the entire Building stock; on the right, the variable distribution across the surrogate model.

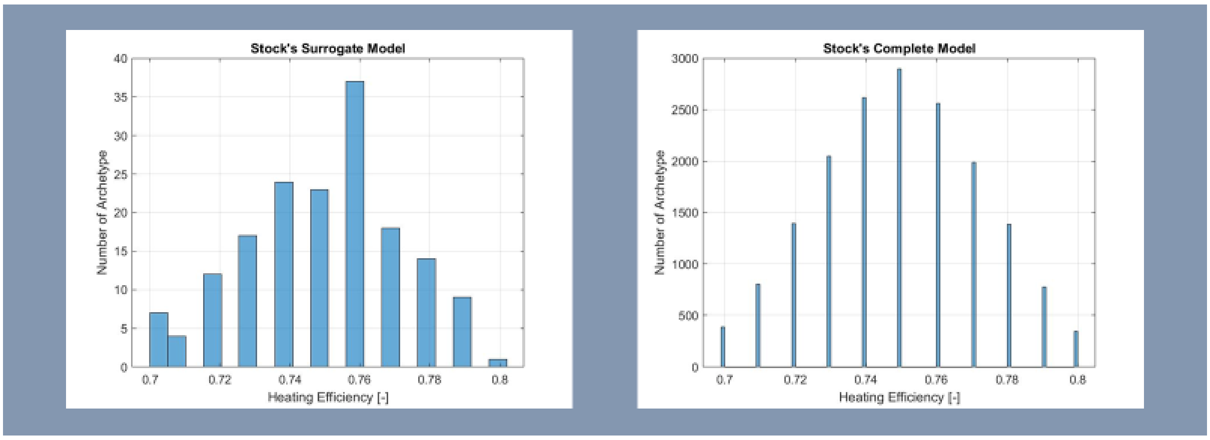

Figure 94:Distribution of the Heating Efficiency. On the left, the variable distribution in case of the entire Building stock; on the right, the variable distribution across the surrogate model.

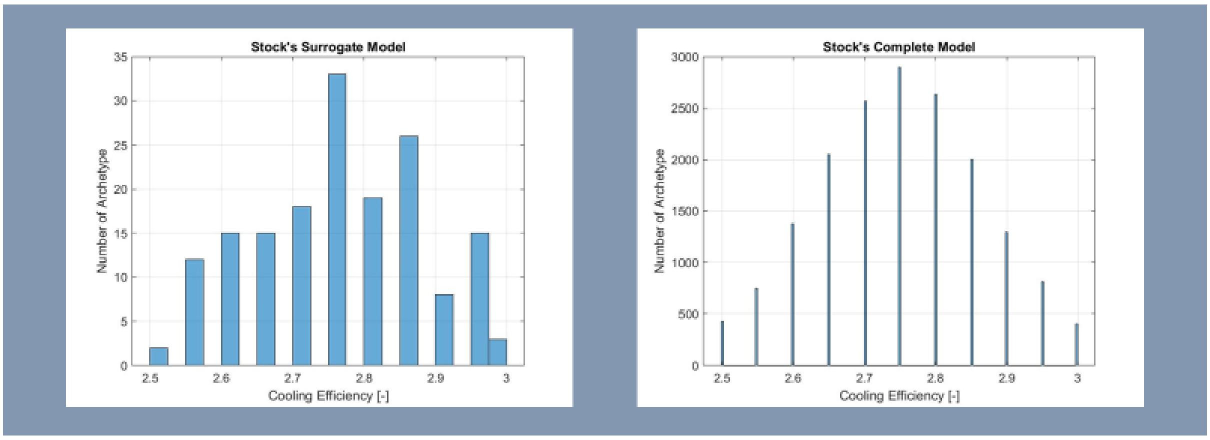

Figure 95:Distribution of the Cooling Efficiency. On the left, the variable distribution in case of the entire Building stock; on the right, the variable distribution across the surrogate model.

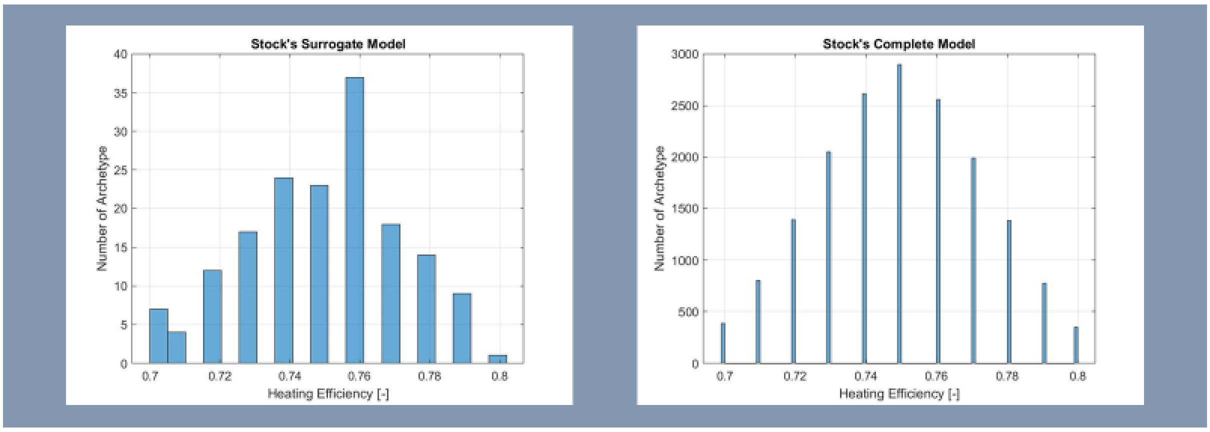

Figure 96:Distribution of the Intermediate floors. On the left, the variable distribution in case of the entire Building stock; on the right, the variable distribution across the surrogate model.