Cost optimal building renovation with a net zero energy target for the Portuguese single-family building stock built before 1960

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ABSTRACT: Cost Optimality and nearly Zero Energy Buildings (nZEB) are two fundamental concepts within the current European Union policy related to the energy performance of buildings and consequently related to climate change mitigation and non-renewable resources consumption. While Cost Optimality is mainly focused on costs, nZEB are focused on low energy consumption levels and on site renewables harvesting.
If the differences between Cost Optimality and nZEB approaches result in major differences in the selection of the best package of renovation measures, the transition from the Cost Optimal concept to nZEB might result incompatible. In this context, using a virtual building representing the Portuguese residential building stock from the 20th century prior to 1960, this study investigates the most cost-effective packages of renovation measures to achieve a zero energy balance building and compares these packages with those resulting from the calculation of cost-optimal levels.
Investigating the trade-offs between a renovation towards zero energy balance and a cost optimal renovation without the use of renewables is relevant to achieve a smooth transition from Cost Optimal levels to nearly Zero Energy Buildings.

1 INTRODUCTION

Climate change observed on the planet is taking an increasingly important role on the society, thus requiring an urgent response at global level (European Commission, 2006).
Since buildings account for about 40% of energy consumption in the European Union, this sector has become an important target for interventions to reduce the greenhouse gases that are released into the atmosphere (European Commission, 2012a).
Within this context, the concept of nearly zero energy buildings arose in the European energy policy as a tool to deal with the need of independence from fossil energy sources and external energy supply (European Parliament, 2010). Energy efficiency and energy harvesting from renewable sources on site or nearby are the essential elements that from the year 2020 on will allow that all new buildings will be nearly zero energy buildings (NAIMA, 2011). However, the long term goals of reducing energy consumption in the European Union for the year 2050 (European Commission, 2011) are impossible to achieve without interventions on the building stock given the very low rate of replacement of the existing buildings by new ones.
The recast of the Energy Performance of Buildings Directive (European Parliament, 2010), besides the definition of Nearly-Zero Energy Buildings, introduced the concept of Cost Optimal levels, which will pave the way of the new energy codes in all EU Member States and their building sector. The concept of Cost Optimal levels is intended to guide Member States on establishing minimum energy performance requirements based on the costs during the entire building life cycle (European Commission, 2012a, 2012b) as opposed to just consider the initial investment cost.
In this context, this paper aims at analyzing the most cost-effective packages of renovation measures to achieve a zero energy balance building and compare these packages with those re-

sulting from the calculation of cost-optimal levels for a typical building representative of the Portuguese housing stock built before 1960. Investigation of the trade-offs between a renovation towards zero energy balance and a cost optimal renovation without the use of renewables is relevant to achieve a smooth transition from Cost Optimal levels to nearly Zero Energy Buildings.

2 METHODOLOGY FOR THE CALCULATION OF COST OPTIMAL LEVELS

The economic viability of a building renovation towards a zero energy balance (for heating, cooling and domestic hot water (DHW) preparation) was determined according to the cost optimal methodology presented by the European Union (European Commission, 2012a).

In order to obtain the cost optimal level for a building renovation it is necessary to test different packages of renovation measures to improve the energy performance of the building and calculate the associated energy needs, the costs to implement those measures and the running costs during the remaining life span of the building.

These packages of measures should be chosen considering that measures applied in a given building element or system can affect the energy performance of other systems. This happens for example when considering different levels of insulation, for which higher insulation means lower heating needs and thus smaller heating devices.

Once defined and calculated the results for each renovation package, it is possible to build a graph based on the use of primary energy and the overall costs associated with the various energy efficiency measures. In this graph a costs curve is created, with the lower points of the curve indicating the packages of measures with the lowest global costs considering the investment costs and the running costs over the entire building life cycle, as demonstrated in Figure 1.

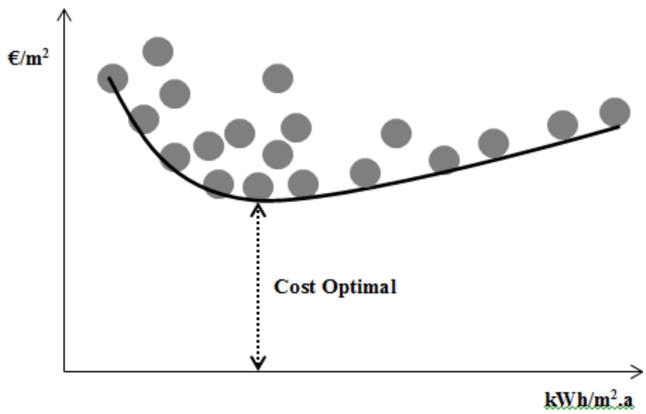

Figure 1 – Cost optimality

Then, with the final goal of obtaining variants of the building with zero energy balance, measures for the use of renewable energy sources are tested. The primary energy use of each variant is balanced with renewable energy and thus allowing to calculate and compare the overall costs associated with each renovation package in order to get the lowest global cost over the building lifecycle.

3 THE CASE STUDY

The building under analysis is representative of the Portuguese residential building stock from a period where energy efficiency was not a concern.

Different efficiency measures in the building envelope and different systems for HVAC and DWH were tested, evolving the building to better energy performance levels and subsequently introducing on-site renewable energy systems (RES).

3.1. Characterization of the reference building

The object of this study is a virtual building that represents the Portuguese existing buildings from the 20th century built before 1960. This building was created based on the data available in the database of the Energy and Indoor Air Quality in Buildings National Certification System (SCE), namely on the dimensions and geometry, construction materials and HVAC and DHW systems. For the location it was assumed the district of Braga, more specifically Guimarães at an altitude of 200 meters.
The selection of the most frequent characteristics of the buildings from this period led to a virtual building that is a single family house with 3 bedrooms consisting of a basement and a ground floor with 80m^2 and floor to ceiling height of 2.7m. Typically the building has lightweight slabs; non-heated attic covered by a wooden roof with ceramic tiles, 50cm thick stone masonry walls with plaster on both sides and windows with wooden frames and single glazing.
The building presents four facades, N, S, E and W oriented, having an average width of 8.94m^2 per facade, a total area of facades of 96.55 m^2 and a total area of glazing of 12m^2, which represents about 12% of the building envelope.
Usually these buildings do not have any insulation, and make use of some simple systems for heating, cooling and preparing hot water. Commonly for DHW preparation a gas water heater is used and electric appliances as fans and electric heaters are used for cooling and heating. Thus, the building presents annual nominal global needs of primary energy in the range of 712kWh/m^2.y to fulfill all the energy needs of the building for heating, cooling and DHW. For this study, the energy needs were calculated following the Portuguese thermal code methodology (Portugal, 2006) and the primary energy use was calculated considering the total energy needs and conversion factors of 2.5kWh$_{PE}$/m^2.y per kWh/m^2.y for electricity and 1kWh$_{PE}$/m^2.y per kWh/m^2.y for gas.

3.2. Identification of different energy efficiency measures

The measures tested were current renovation measures in the Portuguese market that are targeted to improve buildings energy efficiency. Thus, 96 different packages of measures were created by changing various factors such as insulation levels and window types, which were combined with six different HVAC and DHW systems.
At the level of the building envelope, various measures that increased the level of thermal insulation were tested. Outer walls measures are based on the application of ETICS system with a polystyrene (EPS) layer with thicknesses that vary from 30mm up to 140mm.
For the roof, it was considered the application of an insulation layer over the slab. The insulation material considered was extruded polystyrene (XPS) and polyisocyanurate (PIR) with various thicknesses (XPS varying from 30 up to 160mm and PIR varying from 80 up to 140mm).
In the basement ceiling, insulation measures included XPS with dimensions varying between 30 to 160mm and PIR varying from 30 to 80mm.
Regarding the windows, new PVC window frames with double glazing and thermal transmission coefficient of 2.00 W/m°C were taken into consideration.
In each package of measures different systems for HVAC and DHW with different efficiency and energy sources were used, such as two heat pumps, one with COP 4.1 and EER 4.0 and another with COP 3.33 and EER 2.68, both for heating, cooling and DHW. Other solutions included HVAC with COP 4.10 and EER 3.50, gas water heater with an efficiency of 86% and an electric water heater with efficiency of 80% both for DHW and a gas boiler with efficiency of 93% for heating and DHW.
Regarding on-site RES, three solutions were tested, namely a biomass boiler with efficiency of 92%, solar thermal collectors and photovoltaic panels for electricity generation.

3.3. Calculation of the global costs

The calculation of the investment costs was done based on a database with the true market values and thus obtaining prices that were comparable with the currently in practice by Portuguese companies. This database is provided by CYPE, SA (http://www.geradordeprecos.info/) and allows obtaining construction costs taking into account the values of all materials as well as the costs associated with installation, removal and maintenance.

Regarding the costs of energy and carbon emissions, the values published by the European Union (http://ec.europa.I/energy/observatory/trends2030/indexen.htm) and the 2010 scenario of the International Energy Agency for the gas were assumed (http://www.worldenergyoutlook.org/publications/weo-2010/). For the costs associated with the price of pellets for the biomass boiler, it was considered the current market price with a future increase of 3% per year. Table 1 presents the costs associated with each source of energy and the production of CO_2 used throughout this study.

Table 1 – Energy and carbon emissions costs

Energy prices (without and with taxes) and CO_2	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040	2041	2042	2043
Electricity (€ cents per kWh)	21	21	22	22	23	23	24	24	24	25	25	25	26	26	26	26	26	26	26	26	26	26	25	25	25	25	25	24	24	24	24
Gas (€ cents per kWh)	7	8	8	8	9	9	9	9	9	10	10	10	10	10	10	10	10	11	11	11	11	11	11	11	11	11	11	11	11	11	11
CO_2 (€ per ton.)	*20*	*20*	*20*	*20*	*20*	*20*	*20*	*20*	*20*	*20*	*20*	*20*	*20*	*35*	*35*	*35*	*35*	*35*	*50*	*50*	*50*	*50*	*50*	*50*	*50*	*50*	*50*	*50*	*50*	*50*	*50*

For the calculation of the overall costs associated with each variant, a discount rate of 6% was used, as suggested by the European Commission (European Commission, 2012a).

3.4. Cost optimal calculations

Analyzing the different renovation packages, those with the lowest global costs within each group of building systems for heating, cooling and DHW preparation have been identified.
Figure 2 shows the global costs and the non-renewable primary energy associated to each renovation package. In Figure 2, each mark represents a different renovation package.
Figure 2 demonstrates that the package of measures with the lowest global costs is associated with the use of a gas boiler for heating and DHW preparation. Although these packages of measures, as well as those with the biomass boiler are not able to provide cooling, the introduction of an equipment only to deal with cooling needs is not usual in residential Portuguese buildings and the low cooling needs that are experienced in most of the country makes such an investment generally unjustified.
Considering the package of measures with systems that also deal with active cooling, the lowest costs are found with the use of a multi-split HVAC system for heating and cooling and a gas heater for DHW preparation. The use of heat pumps lead to low non-renewable primary energy use, but their initial costs compromise their economic performance even considering the entire life cycle of the building. However, attention should be paid to the fact that the two most cost effective packages of systems for HVAC and DHW require the availability of the natural gas grid, which doesn't cover all areas of the country. If natural gas is not available, the packages of measures using the multi-split HVAC system combined with electric heater for DHW, the biomass boiler and the heat pump with COP 4.1 and EER 4.0, all present very similar global costs with huge differences in the non-renewable primary energy use (128kWhm^2.a for the HVAC, 56kWhm^2.a for the heat pump, and 0kWh/m^2.a for the biomass boiler).

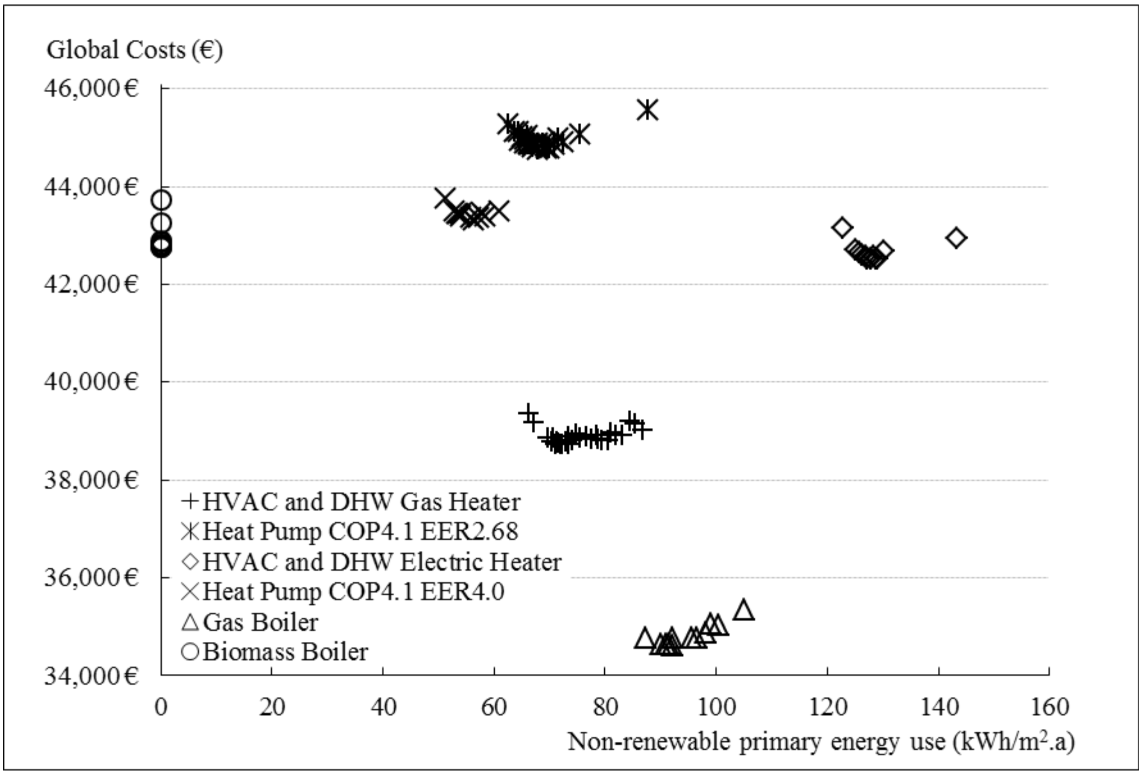

Figure 2 – Cost optimality evaluation without costs or energy restrictions

3.4. Impact of renewables on the cost effectiveness of HVAC and DHW systems

After this analysis, the use of on-site RES has been tested, with the introduction of a solar thermal system to reduce the energy needs to prepare DHW and photovoltaic panels to generate electricity in a quantity that equals the non-renewable primary energy use and thus, transforming the renovated building into a building with a zero non-renewable primary energy use for heating, cooling (when provided) and DHW preparation.
The contribution of the thermal solar system was calculated with the SOLTERM 5.0 software and the calculation of the photovoltaic power (kWp) required to generate the needed electricity was calculated using the online tool PVGIS (http://re.jrc.ec.europa.eu/pvgis/apps4/pvest.php #), made available by the European Union, which takes into consideration factors such as the orientation of the photovoltaic panels, the slope and the location.
In Figure 3, the various packages of measures with a zero non-renewable primary energy use are presented associated to their global costs. Figures 2 and 3 shows that the hierarchy of cost effectiveness from the several HVAC and DHW systems didn't suffer major modifications with the use of on-site RES. Only for the two solutions using multi-split HVAC for heating and cooling a relevant approximation happens. In fact, with on-site RES, the use of an electric heater or a gas heater for DHW becomes almost equivalent, certainly due to the significant reduction of energy needed to increase the water temperature by the effect of the solar thermal system.

Again with the exception of the strong effect in the DHW system using an electric heater, also the differences in global costs between the several HVAC and DHW systems are similar with those obtained in the analysis without on-site RES.
Considering these results it is possible to conclude that the installation of on-site RES doesn´t change significantly the hierarchy of cost effectiveness between the different HVAC and DHW systems.

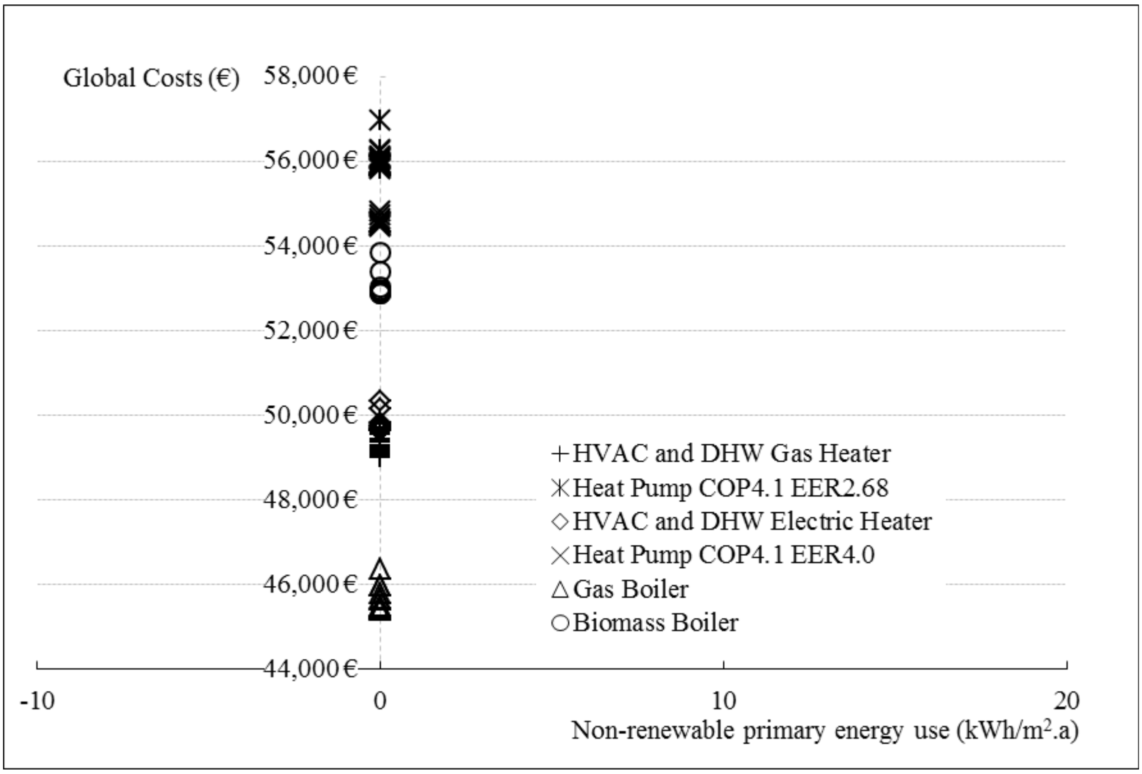

Figure 3 – Cost optimality evaluation towards zero non-renewable primary energy use

3.5. Impact of renewables on the cost effectiveness of envelope elements

The impact of on-site RES on the cost effectiveness of measures on the building envelope has also been tested.

Figure 4 presents all packages of measures to improve the building envelope in which the gas boiler has been used for heating and DHW preparation. Each mark represents a building renovation variant (VAR) with its non-renewable primary energy use and global costs.

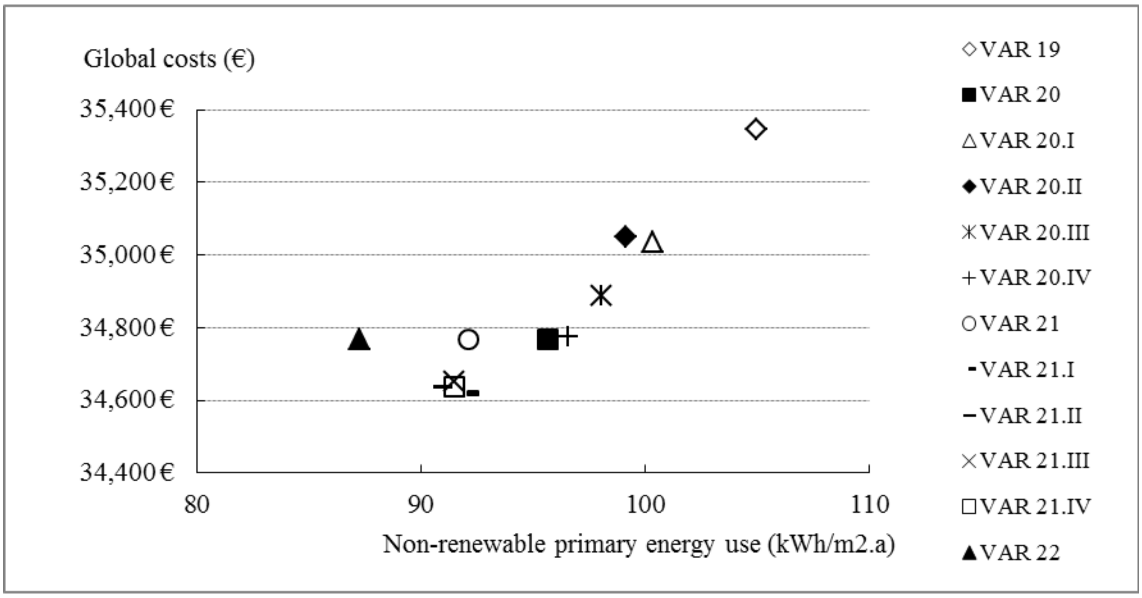

Figure 4 – Cost optimality evaluation with the use of gas boiler for heating and DHW preparation

The cost optimal package of measures, identified as VAR 21.I, includes ETICS in the outer walls with a 100mm thick layer of EPS; a 140mm thick layer of PIR on the ceiling; a 50 mm thick layer of PIR in the basement ceiling; and PVC frames with double glazing in windows.
After the introduction of thermal solar and photovoltaic panels to obtain a zero non-renewable primary energy balance, the package of measures leading to the optimal cost is a slightly more efficient one, as can be seen in Figure 5. In this case, the package of measures with the lowest global cost is identified in Figure 5 as VAR 21.IV - ER and includes ETICS in the outer walls with a 120mm thick layer of EPS; a140mm thick layer of PIR on the ceiling slab; a 50mm thick layer of PIR in the basement ceiling; and PVC frames with double glazing in windows.
The package of measures with the lowest global cost, when the goal is zero non-renewable primary energy balance, presents a level of insulation in the exterior facade slightly above the value of the renovation package that led to the optimal cost without the zero energy target. This package, due to the high investment costs in on-site RES, has an associated global cost of approximately €10,800 higher than the cost optimal package without renewables, which means an increase of nearly 30% of the global costs and an increase of nearly 50% in the investment costs.

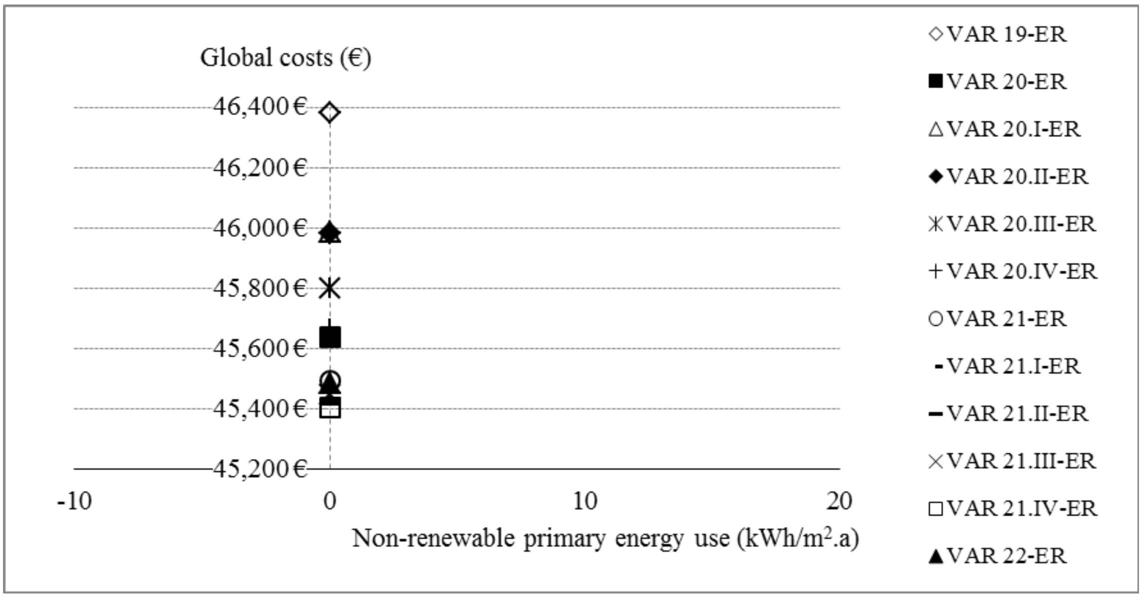

Figure 5 – Cost optimality evaluation with zero non-renewable primary energy use with the use of gas boiler for heating and DHW preparation

Analyzing the other systems for HVAC and DHW, the variations are very similar to the ones presented for the gas boiler. In the case of the multi-split HVAC with the electric heater for DHW and also in the case of the biomass boiler for heating and DHW, a change in the package of measures with the lowest global cost occurs for a package of measures with a slightly better energy performance. In the case of the heat pumps and also in the case of the multi-split HVAC with a gas heater for DHW, the cost optimal package is also the package with the lowest global cost in the evaluation for zero non-renewable primary energy use.
Considering these results it is possible to conclude that the installation of on-site RES doesn´t change significantly the hierarchy of cost effectiveness between the different packages of measures in the building envelope. Nevertheless, there is a clear tendency for the reduction of the gap in global costs between the cost optimal package of measures and those with better energy performance and in some cases the lowest global costs are obtained with packages with slightly better energy performance.

4 CONCLUSIONS

The results presented in this article are part of a broader ongoing work that will consider single-family buildings from different periods and in different locations in Portugal. Although actual results are only referring to a single building type and location, they already allow drawing some conclusions concerning the cost effectiveness of the combination of measures to improve the energy performance of the building envelope and of the HVAC and DHW systems and the use of on-site harvested renewable energy to achieve a zero energy balance.

Without the restriction of zero energy balance, the cost optimality is found for packages of measures using natural gas, if only for DHW or also for heating. If natural gas grid is not available, the packages of measures using a multi-split HVAC system combined with electric heater for DHW, the biomass boiler or the heat pump, all present very similar global costs with significant differences in the non-renewable primary energy use. In these cases of similar global costs, the building variants with the lowest non-renewable primary energy should be chosen.

With the introduction of a solar thermal system to reduce the DHW energy needs and photovoltaic panels to generate electricity in a quantity that equals the non-renewable primary energy use, the hierarchy of cost effectiveness from the several used HVAC and DHW systems, didn't suffer major modifications. An exception has been observed in the synergy with the packages of measures using an electric heater for DHW, certainly due to the significant reduction of the energy needed to increase the water temperature by the effect of the solar thermal system, reducing the impact of the use of a low efficient system such as the electric DHW heater.

Considering the impact of the use of on-site RES on the cost effectiveness of the measures in the building envelope, it is possible to conclude that although their use doesn´t change significantly the hierarchy of cost effectiveness between the different packages of measures, there is a tendency for the reduction of the gap in global costs between the cost optimal package of measures and those with better energy performance. In some cases the lowest global costs are obtained with packages with slightly better energy performance than the cost optimal package without a zero energy restriction.

The actual results, which are to be confirmed with studies on other buildings from different periods and located in other parts of the country, point out to a robustness of the cost optimal methodology in the definition of the most cost effective packages of measures in the building envelope, with very similar results for a zero non-renewable primary energy goal or without this restriction. Nevertheless, a cost optimal range instead of a cost optimal single package should be considered, once some combinations of HVAC and DHW systems and on-site RES, shift the cost optimal envelope package to a different one with slightly better energy performance.

Complementary, these results also point out to synergies between the use of on-site RES and the DHW systems, allowing the choice of simpler equipments with a lower investment cost and reducing the impact of the use of electricity as the energy vector in the quantification of the non-renewable primary energy.

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