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Article

Relevance of Embodied Energy and Carbon Emissions on Assessing Cost Effectiveness in Building Renovation—Contribution from the Analysis of Case Studies in Six European Countries

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Received: 12 July 2018; Accepted: 8 August 2018; Published: 9 August 2018

Abstract: The construction sector is facing increasingly strict energy efficiency regulations. Existing buildings have specific technical, functional and economic constraints, which, in fulfilling regulations, could lead to costly and complex renovation procedures and also lead to missed opportunities for improving their energy performance. In this article, the methodology for comparing cost-optimality in building renovations, developed in the International Energy Agency (IEA)–Energy in Buildings and Communities (EBC) Annex 56 project, is extended with a life cycle assessment by including embodied primary energy and carbon emissions in the calculations. The objective is to understand the relevance of embodied energy and carbon emissions in the evaluation of the cost effectiveness of building renovation solutions towards nearly zero energy buildings, as well as the effect of the embodied values in the achievable carbon emissions and primary energy reductions expected in an energy renovation. Results from six case studies, representative of different regions in Europe, suggest that embodied values of energy and carbon emissions have a decreasing effect—ranging from 2 to 32%—on the potential reductions of energy and emissions that can be achieved with renovation measures in buildings. In addition, the consideration of the embodied energy and carbon emissions does not affect the ranking of the renovation packages.

Keywords: cost-optimal; IEA-EBC Annex 56; building renovation; life cycle assessment

1. Introduction

European buildings are responsible for about 40% of the EU's final energy consumption, with 60% of this consumption being electricity-related [1]. Importantly, the energy consumed by buildings creates a significant share of the carbon emissions that are released into the atmosphere every year [2]. In an attempt to prevent the escalation of these problems, the European Commission has released and revised several regulations and developed several initiatives in order to promote energy efficiency and the reduction of carbon emissions. The Energy Performance of Buildings Directive (EPBD), recast in 2010, was a turning point in which new concepts were introduced, namely the cost optimal concept and nZEB (nearly zero energy buildings) [3]. Although the current tools and regulations mainly target new constructions and large building renovations, there is an increasing recognition of the need to tackle the existing building stock. Existing buildings, which in Europe are on average more than 20 years old and present, in general, poor energy performance [4], have a replacement rate of around 1 to 2% per year [5], which is clearly insufficient in order to meet the EU 2030 and 2050 goals.

Existing buildings have several technical, functional and economic constraints, and applying the regulations targeted to new buildings to the existing ones can lead to costly and complex renovation procedures, which are hardly accepted by the owners or promoters. This fact may contribute to missed opportunities for improving the buildings' energy performance. Investment costs concerning building renovations are likely to increase as the depth of the intervention increases and new materials and building integrated technical systems (BITS) are added to the building [6]. It is necessary then to address the trade-offs between the costs and effectiveness of interventions regarding energy performance improvements in existing buildings. For that purpose, the International Energy Agency (IEA), in the scope of the Energy in Buildings and Communities programme (EBC), launched the Annex 56 project for cost effective energy and carbon emission optimization in building renovation, in which the authors participated [7,8]. The project aimed at developing a general framework for comparing the cost-effective renovation of existing buildings, combining energy efficiency measures and the use of energy from on-site renewable sources. The methodology developed within Annex 56 is intended to be used by private entities and governmental agencies to help in the decision-making process of renovating a building. This methodology was developed to be applied in residential and low-tech office buildings. The methodology balances the primary energy demand and the global costs of each renovation scenario in order to compare them using a life cycle approach as established by the EU Delegated Regulation nº 244/2012 [9]. This perspective differs significantly from the common approach to the subject, which focusses only on energy during the operation phase [10].

There are several different approaches to this methodology in relation to the renovation of different types of buildings, such as historic buildings (e.g., [11]) and public buildings (e.g., [12]). Analysis concerning renovation towards nZEB buildings—independently of the programmatic function—can also be found and clearly show not only the relationship between the concept of nZEB and economic performance [13] but also the applicability of the concept in terms of differences in geographical and national contexts [8,14–16], as well as the advantages of renovating buildings up to this level in terms of resilience to future climates [17].

Although life cycle assessment (LCA) has been used in the building sector since the 1990s [18], the sustainable construction movement and its need to objectively assess the environmental impact of construction practices has strengthened the use of this approach. LCA has already been used in several studies focusing on building renovation (e.g., [19–21]), even if, according to a review by Cabeza et al. [22], the majority of the studies have been performed in what the authors call "exemplary buildings", i.e., buildings that have been constructed already with the purpose of being sustainable and using low amounts of energy. In addition, studies taking an environmental assessment perspective of cost-optimal solutions for building renovation are scarce and geographically inconsistent. Previous research includes multidimensional Pareto optimization using LCA in three residential buildings located in France, Sweden and The Netherlands [23], an optimization matrix development for a multistorey residential building in Northern Italy [24] and an integrated life-cycle assessment and cost optimality assessment at a historic building in Portugal, which showed that these kind of buildings (which do not have to comply with energy and thermal codes) can achieve significant energy savings (taking into consideration also economic and environmental costs) [25].

Besides the life cycle cost analysis, the methodology developed in the Annex 56 project also allows the inclusion of LCA (life cycle assessment), balancing the energy used in the operation phase and the embodied energy and the carbon emissions associated to the materials used [26]. In that context, this paper focus on the comparison of several case studies regarding the significance of LCA, in particular embodied energy and embodied carbons emissions, while evaluating the cost effectiveness of energy renovation measures in buildings in different national contexts. In particular, the study aims to investigate whether considering environmental performance in cost effectiveness calculations of building renovation measures can lead to different outcomes.

The Significance of Considering Environmental Performance in Building Renovation

The environmental performance of the existing buildings is directly related to the materials that are added to the building and to the energy that is spent in the process. Thus, theoretically, the impact of building renovation should be smaller when compared to the construction of new buildings where bigger amounts of materials are involved [26].

In building renovation, it is important to balance the initial impact of the materials that are going to be added when intervening with the building and the effect of those on the subsequent building operation; in particular regarding the energy use. In fact, when a building is renovated, namely with the objective of improving its energy efficiency, there is a significant upscale in costs and impacts due to the implementation of new materials and technical systems. As a rule of thumb, it can be stated that the more ambitious the energy renovation is, the higher the costs and impacts of the intervention itself are, but the lower the costs and impacts in the subsequent building operation phase [26], as summarized in Figure 1.

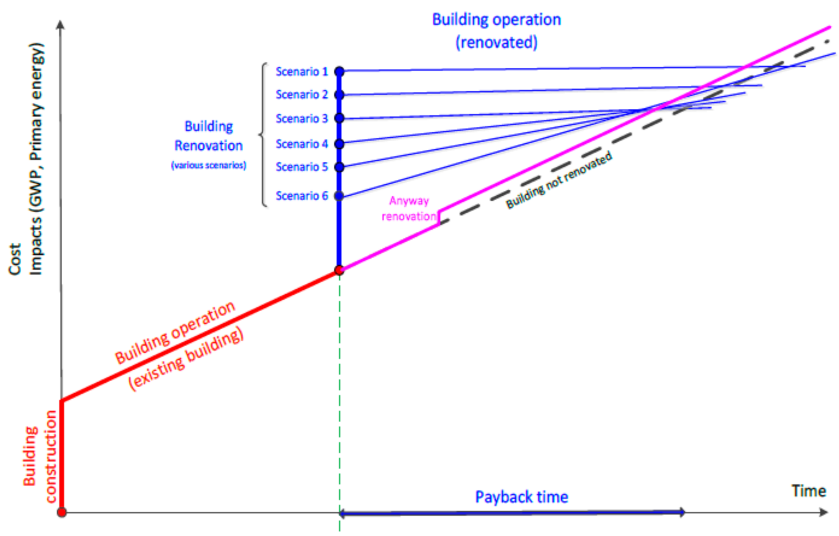

Figure 1. Representation of the effect of energy related renovation measures compared to the existing situation. Source: [26]. GWP: Global warming potential.

These impacts and the weight of the embodied energy and carbon emissions in the renovation intervention are highly dependable on the target set as the objective for the intervention. In a building renovation, and in order to reduce the primary energy used in building operation, both a minimization of demand (by intervening in the building envelope and/or increasing building integrated technical systems' (BITS) energy efficiency) and the use of renewable energy sources are significant. However, it has to be considered that each of these measures will also imply an amount of embodied energy related to the materials added or to the BITS, as shown in Figure 2.

The figure also stresses the fact that the more energy is minimized, the more embodied energy is likely to be needed. When the objective of a building renovation is to reach a nearly zero target, this issue is even more pressing, because of the relevant use of renewable energy systems [6].

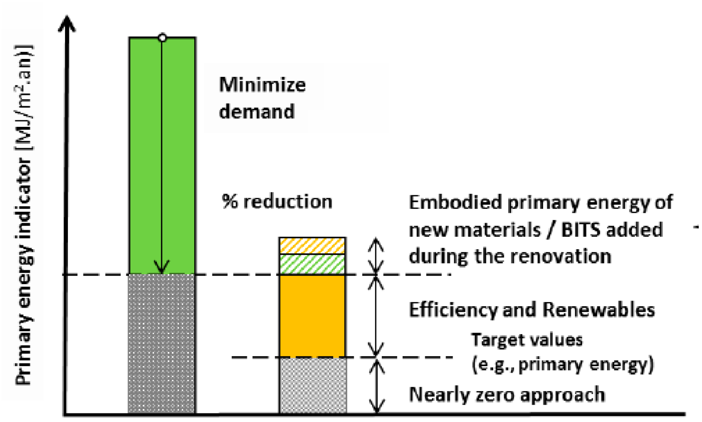

Figure 2. Effect of energy renovation measures in terms of embodied energy. Source: [26]. BITS: Building integrated technical systems.

2. Methodology

2.1. Cost Optimal Methodology

The methodology developed within Annex 56 [8] establishes a general framework for the comparison of renovation packages, considering the balance between energy savings, carbon emission reduction and global costs, while also considering the co-benefits associated with each renovation package. However, the focus of this paper is related to the evaluation of the impact of the embodied carbon emissions and embodied energy in the final primary energy use, and thus the co-benefits analysis is not addressed in this context.

The methodology is based on the comparison of several renovation scenarios with a reference case, known as "anyway renovation". "Anyway renovation" is a renovation where the energy performance of the building is not improved, dealing simply with aesthetical, functional and structural issues. The reference case is also useful to establish the threshold for the cost effectiveness of renovation scenarios. If a renovation scenario presents a lower energy demand and lower costs than the reference case, it is considered cost effective to be implemented in the building. The renovation packages considered in the analysis should be designed to include improvements in the buildings elements and also in the BITS. The comparison between the renovation packages requires the calculation of the energy use associated with each of them as well as the calculation of the related carbon emissions and global costs.

The method for energy calculation is flexible, but it should be used in accordance with local thermal regulations, given the diversity of climatic conditions and construction characteristics where it could be applied.

The global costs must include all costs: Namely investment costs, maintenance costs, energy costs, replacement and disposal at the end of the calculation period. The calculations should typically consider a life cycle of 30 to 60 years. This procedure is in line with the cost-optimal calculations predicted by the EU Delegated Regulation nº 244/2012 [9] as a complement to the recast of the Energy Performance of Buildings Directive (EPBD-recast) [3]. The future cost must also be predicted and brought to the present moment of calculation, which can be achieved by applying the net present value or the annuity methods. Within the Annex 56 case studies, the annuity method was preferred, and it is the one presented here.

The results of the comparison of the different renovation packages can be illustrated with the help of graphs, where the x-axis presents the primary energy use and the y-axis presents the global costs (Figure 3). More details can be clarified in the published article focusing on the methodology used in the scope of the project [8]).

2.2. Life Cycle Assessment

In order to expand the Annex 56 methodology, it is necessary to take an LCA approach to incorporate the impacts of the renovation materials. Because the focus of the analysis is the energy-related measures applied in buildings, the LCA assessment will only take into account measures that affect the energy performance (thermal envelope, building integrated technical systems and energy use for on-site production and delivered energy). The methodology concerning the LCA analysis is detailed in the corresponding Annex 56 report: Life cycle assessment methodology for energy-related building renovation [26].

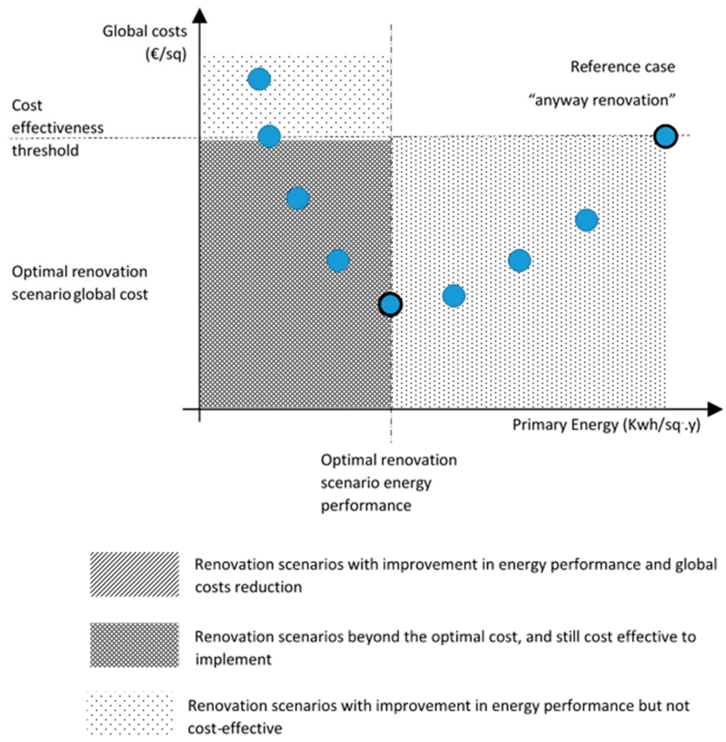

Figure 3. Demonstration of the cost optimal calculations according to the methodology. Source: Adapted from [8].

In the context of the Annex 56 methodology, and concerning the life cycle assessment (LCA), many indicators could be taken into consideration. However, the methodology consists in comparing different renovation packages and analyzing many indicators, which could become very time-consuming. Thus, the number of indicators used in the analysis were restricted to three: namely carbon emissions represented by the global warming potential (GWP) (quantifying the amount of CO_2 involved in each renovation package), cumulative non-renewable primary energy demand (NRPE) and cumulative total primary energy demand (TPE). These indicators were chosen due to their good correlation with the remaining environmental indicators considered in the LCA method [27] and with the cost optimal methodology.

In order to perform a LCA analysis, it is fundamental to define system boundaries. There are two types of system boundaries to be defined: the temporal boundary (defining elementary stages, occurring during the life of the building) and the physical boundary (where materials and energy flows are defined).

In terms of the temporal boundary, in this analysis, the main stages of the building life cycle are defined following the EN 15978 standard [28]. The different stages can be defined as follows: (1) Material production stage, which configures the cradle to grave processes for the manufacturing of the materials used in construction processes and technical systems to obtain the final products delivered at the gate of the factory; (2) the building construction processes stage, which includes the transportation of necessary materials and equipment (e.g., cranes, scaffoldings), as well as all the processes needed for the renovation of the building.; (3) the building use stage, which concerns the period that the building is used by the occupants, i.e., until the deconstruction of the building, including maintenance, repair and replacement of materials, as well as the energy used by technical systems.; (4) the building end of life stage, which covers the processes included in the building demolition and material elimination, including waste transport and management. In this stage, it is important to clarify that the calculations carried out for each of the case studies considered the transport and management of the waste. However, the type of waste processing and disposal considered depended not only on the national context but also on the materials in the building. Therefore, after the decommissioning of the building, the materials can be processed in different ways (recycled, reused, incinerated or dumped in a landfill, for example). Each stage uses energy and materials and also releases air, water and soil emissions. Not all of the stages contribute in the same extent to the life cycle impacts of the building.

In terms of physical boundaries, in this study, the LCA of a renovated building includes the following elements: The materials added for energy-related renovation measures of the thermal envelope of the building; the materials added for energy-related renovation measures for the building integrated technical systems (BITS), including on-site energy generation units (PV, solar thermal, etc.); and the materials added to provide the same building function before and after renovation. The construction elements are composed of one or more materials, generally assuming a layered composition. BITS consist of several different components which are fabricated from distinctive materials. Both construction elements and components in BITS use one or more energy vectors. The service life of materials, i.e., the time during which a building component fulfils its function, depends on the type of construction element (wall, floor, roof, etc.), the situation of the construction element (against ground, exterior and interior) and the position of the material layer within the construction element. Table 1 demonstrates the aspects to be included in the LCA of a building renovation.

Table 1. Aspects to be included in a building renovation. Source: Adapted from [26].

<table>
<tr><td rowspan="8">Energy used by technical systems after renovation</td><td>Home appliances (Oven, refrigerator, TV ...)</td><td>Not considered in the methodology</td></tr>
<tr><td>Common appliances (lifts, escalators ...)</td><td>Optional in the methodology</td></tr>
<tr><td>Heating</td><td rowspan="9">Mandatory in the methodology</td></tr>
<tr><td>Domestic hot water</td></tr>
<tr><td>Air conditioning</td></tr>
<tr><td>Ventilation</td></tr>
<tr><td>Lighting</td></tr>
<tr><td>Auxiliary</td></tr>
<tr><td rowspan="2">Materials added and replaced for energy related renovation measures of building envelope</td><td>Materials for the building envelope (windows, thermal insulation ...)</td></tr>
<tr><td>Materials replaced to provide the same function (balcony, cladding, ...)</td></tr>
<tr><td>Materials added and replaced for energy related renovation measures of the building integrated technical systems</td><td>Materials for energy production and distribution (Boiler, PV panels, bore-hole, pipes, radiators, ...)</td></tr>
</table>

To calculate the impact of each renovation package, it is necessary to calculate the amount of materials involved and multiply them by the related impacts. The same happens with the energy, which has to be multiplied by the related impact by energy carrier. In this analysis, the LCA for building renovation, taking into account materials and BITS as well as the operational primary energy use, is calculated as follows:

$$PE_{building} = PE_{materials} + PE_{BITS} + PE_{op\ energy\ use} \quad (1)$$

where

$PE_{building}$ is the primary energy of the building renovation;
$PE_{op\ energy\ use}$ is the calculated primary energy for the operational energy use;
PE_{BITS} is the primary energy of the BITS;
$PE_{materials}$ is the primary energy of all materials which were used in the building renovation.

The same equation is used for the carbon emissions. This being so, in order to differentiate the primary energy demand (and carbon emissions), which considers the different stages in building life cycle, the terms "embodied primary energy" and "embodied carbon emissions" will be applied.

It is important to highlight that the methodology for LCA does not impose a specific calculation software or database. It only requires the use of recognized and reliable sources for the quantification of the chosen indicators. Therefore, the LCA was carried out through the use of spreadsheets or existing LCA tools, depending on national contexts, such as the Swiss Eco-Bat [29] or by adapting existing tools, e.g., the ASCOT tool [30,31] developed for Denmark.

In the context of the methodology used in this study, both LCA and Life Cycle Costs (LCC) were carried out for a study period of 60 years, for which all contributions of materials and energy consumptions are calculated. The study period is determined by having to be equal or longer than the service life of the energy related building components analyzed.

In order to ensure a consistent implementation of the LCA methodology in the six detailed case studies (which are detailed in the next section), an inter-comparison of LCA tools and spreadsheets used by the different partners was conducted on a simple case study. The goal of this preliminary exercise was to check if each partner was able to get the same results using different tools for the calculations. The detailed description can be consulted in the Appendix 2 of the Annex 56 "Life Cycle Assessment" report [26].

3. Case Studies

For this study, interventions in six buildings were analyzed. The selected case studies where the methodology was applied are constituted by five residential buildings and one elementary school. The main criterion for choosing the case studies within the national contexts was the fact that the buildings were recently renovated, preferably in the last five years before the analysis. The main reasons for the renovation were maintenance and the improvement of standards and the energy efficiency of the building. The depth of the renovation was dependent on the condition of the building prior to the intervention. Thus, a wide range of different renovation measures can be found in the case studies. However, significant improvements in the insulation level of the envelope and the replacement of building integrated systems (including the integration of renewable energy sources) are common measures across all case studies. The analysis reported here was realized after the intervention and the theoretical renovation packages considered in the study were defined in order to be compared with the actual intervention. The buildings are representative of different climates and national contexts in Europe, since they include two buildings from northern Europe, two from central Europe and two from southern Europe. These buildings were built between 1950 and 1987 and presented different types of anomalies requiring different types of renovation solutions. Table 2 presents a summary of the analyzed building, by participating country.

Table 2. Overview of the case studies: Adapted from [26].

Country	KGC *	Before	After	Site	Building Type	Year of Construct	Year of Renovation	GHFA *1 (m^2)
Austria	Dfb			Johann-Böhmstraße, Kapfenberg	Multi-family building	1960–1961	2012–2014	2845
Denmark	Cfb			Traneparken, Hvalsø	Multi-family Building	1969	2011–2012	5293
Sweden	Cfb			Backa röd, Gothenburg	Multi-family Building	1971	2009	1357
Czech Republic	Cfb			Kamínky 5, Brno	Elem. School	1987	2009–2010	9909
Portugal	Csb			Neighbourhood RDL, Porto	Two-family Building	1953	2012	123
Spain	Cfb			Lourdes Neighbourhood Tudela	Multi-family Building	1970	2011	1474

* KGC—Köppen–Geiger Classification. *1 GHFA—Gross heated floor area.

Concerning the renovation measures, it was established that each country had to analyze three renovation packages for the building envelope in addition to the reference case: Two alternatives with increasing thicknesses of the insulation and the chosen renovation package (the one that was implemented).

The two alternative renovation solutions had to be combined with four different BITS for heating, cooling and domestic hot water (DHW). It was necessary to analyze at least one combination of BITS with a renewable energy source (RES), such as biomass.

For the envelope, most packages included the addition of insulation in the walls, roof, and floor. In the northern countries, the buildings already had insulation, so the renovation packages consisted in increasing the insulation level. The windows in the northern countries were in most cases triple-glazed, and they were double-glazed in Portugal and Spain (Table 3).

In the case of the Czech Republic, since it was a school building with high rates of occupancy during the day, the quality of the air was a problem, so a new ventilation system was added.

Table 3. Renovation packages: adapted from [32].

Case Study	Reference Case	Renovation Measures	
	V1	V2	V3—Implemented
Austria	**Façade:** Painting outside walls **Windows:** Painting and repair of wooden frame windows **BITS:** Central Heating and Domestic Hot Water production **Energy Sources:** Oil **RES:** None	**Façade:** 80 mm EPS **Roof:** 200 mm EPS **Windows:** Double glazed with external shading system **BITS:** Central heating and domestic hot water production **Energy sources**: Oil/natural gas/wood/DH with RES **RES**: None	**Façade:** 240 mm EPS **Roof:** 300 mm EPS **Windows:** Triple glazed with external shading system **BITS:** Central heating and domestic hot water production. Mechanical Ventilation with heat recovery (SFP = 1.62, Eff. = 65%) **Energy Sources:** Oil/natural gas/wood/DH with RES **RES:** None	**Façade:** Walls insulated with prefabricated wood modules (240 mm) **Roof:** 300 mm EPS **Windows**: Triple-glazed windows (with an external shading device) **BITS:** New central heating and domestic hot water production. New mechanical ventilation system with heat recovery (SFP = 1.62, Eff. = 65%) **Energy Sources:** District heating based on renewables **RES:** 144 m^2 solar thermal system for heating and DHW production. 92 kWp PV system for electricity generation on-site
Denmark	**Façade:** Maintenance of the outer skin of external walls **Roof:** New Roofing **Windows:** Painting and repair of wooden windows **BITS:** Renewal of the heating and domestic hot water system **Energy Sources:** District heating based renewables with a share of 53% **RES:** none	**Façade:** 100 mm insulation **Roof:** 450 mm insulation **Windows:** Triple-glazed low-e windows **BITS:** Renewal of the heating and domestic hot water system. New mechanical ventilation system with heat recovery (SFP = 1.2, Eff. = 90%) **Energy Sources:** Oil/natural gas/DH with 53% RES **RES:** 33 kWp photovoltaic system for the electricity generation on-site	**Façade:** No intervention **Roof:** 450 mm insulation **Windows**: Triple-glazed low-e windows **BITS:** Renewal of the heating and domestic hot water system. New mechanical ventilation system with heat recovery (SFP = 1.2, Eff. = 90%) **Energy Sources:** Oil/natural gas/DH with 53% RES **RES:** 132 kWp photovoltaic system for the electricity generation on-site	**Façade:** 211 mm insulation **Roof:** 250 mm additional roof insulation **Windows:** Triple-glazed low-e windows **BITS:** Renewal of the heating and domestic hot water system. New mechanical ventilation system with heat recovery (SFP = 1.4, Eff. = 80%) **Energy Sources:** DH with 53% RES **RES:** 33 kWp photovoltaic system for the electricity generation on-site
Sweden (Sweden (cont.)	**Façade:** Maintenance of the façade **BITS:** New district heating substation, for heating and new recirculation for domestic hot water installed **Energy Sources:** District heating partly (81%) based on renewables **RES:** None	**Façade:** 100 mm insulation **Roof:** 100 mm insulation **Windows:** Triple glazed windows (U-value 1.7 W/m^2K) **BITS:** Balanced mechanical ventilation system with heat recovery (Eff. = 50%) **Energy Sources:** Oil/natural gas/electricity/DH **RES:** No intervention	**Façade:** 195 mm insulation **Roof:** 300 mm insulation **Windows:** Triple glazed windows (U-value 0.9 W/m^2K) **BITS:** New low-energy lighting **Energy Sources:** Oil/natural gas/electricity/DH **RES:** No intervention	**Façade:** 195 mm insulation **Roof:** 300 mm insulation **Windows:** Triple glazed windows (U-value 0.9 W/m^2K) **BITS:** Balanced mechanical ventilation system with heat recovery (Eff. = 50%). New low-energy lighting **Energy Sources:** District heating partly (81%) based on renewables **RES:** No intervention

Table 3. *Cont.*

Case Study	Reference Case	Renovation Measures	
	V1	V2	V3—Implemented
Czech Republic	**Windows:** Double and triple glazed. **BITS:** New mechanical ventilation system with heat recovery in the kitchen, storage rooms, toilets and showers New heating system including new storage tank for DHW. **Energy Sources:** District heating based on natural gas **RES:** None	**Façade:** 90 mm EPS **Roof:** 90 mm EPS **Windows:** Double and triple glazed. **BITS:** New mechanical ventilation system with heat recovery in the kitchen, storage rooms, toilets and showers New heating system including new storage tank for DHW. **Energy Sources:** District heating based on natural gas /electricity **RES:** Installation of a 66.42 kWp photovoltaic system for the electricity generation on-site	**Façade:** 290 mm EPS **Roof:** 300 mm EPS **Windows:** Triple glazed. **BITS:** New mechanical ventilation system with heat recovery in the kitchen, storage rooms, toilets and showers. New heating system including new storage tank for DHW. **Energy Sources:** District heating based on natural gas/natural gas/electricity **RES:** Installation of a 66.42 kWp photovoltaic system for the electricity generation on-site	**Façade:** 160 mm EPS **Roof:** 180 mm EPS **Windows:** Double and triple glazed. **BITS:** New mechanical ventilation system with heat recovery in the kitchen, storage rooms, toilets and showers New heating system including new storage tank for DHW. **Energy Sources:** District heating based on natural gas/natural gas/electricity **RES:** Installation of a 66.42 kWp photovoltaic system for the electricity generation on-site
Portugal (cont.)	**Façade:** Maintenance of outside walls **Roof:** Maintenance of the roof **Windows:** Maintenance of existing windows **BITS:** Renewal of the existing electrical heating and domestic hot water systems HVAC system for Cooling **Energy sources:** Electricity **RES:** None	**Façade:** 100 mm EPS **Roof:** 140 mm rock wool **Windows:** No intervention **BITS:** Replacement of the heating and domestic hot water system **Energy Sources:** Electricity/natural gas/biomass **RES:** 3.8 m^2 solar thermal panels for DHW 3.7 kWp photovoltaic panels	**Façade:** 80 mm cork board insulation **Roof:** 80 mm cork board insulation **Windows**: Double Glazed **BITS:** Replacement of the heating and domestic hot water system **Energy Sources:** Electricity/natural gas/biomass **RES:** 3.8 m^2 solar thermal panels for DHW 3.7 kWp photovoltaic panels	**Façade:** 60 mm EPS **Roof:** 50 mm XPS **Windows:** Double glazed **BITS:** Replacement of the heating and domestic hot water system **Energy Sources:** Electricity **RES:** 3.8 m^2 solar thermal panels for DHW
Spain	**Façade:** Maintenance of existing façade **Roof:** Maintenance of existing roof **Windows:** Maintenance of single-glazed windows **BITS:** New central heating system for heating and domestic hot water production. **Energy Sources:** Oil **RES:** None	**Façade:** 40 mm EPS **Roof:** 40 mm XPS **Windows:** Double glazed **BITS:** Replacement of the heating and domestic hot water system **Energy Sources:** Oil, electricity/natural gas/DH with RES and gas (75%/25%) **RES:** None	**Façade:** 220 EPS **Roof:** 240 EPS **Windows:** Double glazed **BITS:** New central heating system for heating and domestic hot water production. New mechanical ventilation system with heat recovery which can be also used to pre-cool the air (SFP = 1.5, Eff. = 75%) **Energy Sources:** Oil, electricity/natural gas/DH with RES and gas **RES:** 26 m^2 solar thermal system for DHW	**Façade:** 60 mm EPS **Roof:** 60 mm XPS **Windows:** Double glazed **BITS:** Renewal of the district heating system **Energy Sources:** DH with RES and gas (75%/25%) **RES:** 11 kWp photovoltaic system for the electricity generation on-site

Abbreviations used in this table: BITS—building integrated technical systems; RES—renewable energy sources; DH—district heating; DHW—domestic hot water; HVAC—heating, cooling and air conditioning; Kwp—kilowatt peak; U Value—thermal transmittance of a building element in W/m^2K; EPS—expanded polystyrene insulation; XPS—extruded polystyrene insulation; SPF—specific fan power ($Kw/(m^3/s)$).

4. Results

Regarding the inter-comparison of the simple case study, the results point to the fact that when partners use the same data, they are able to get similar results. In the results provided by the participating countries, the relative deviations found were less than 5% and, therefore, is it assumed that the LCA methodologies can be used with confidence in order to compare the results of the different case studies.

Concerning the case studies from the participating countries, after the LCC and LCA assessment, it was possible to establish graphs with the results of the calculated indicators. The global costs of both analyses are equal and the difference between them relies on the embodied energy and embodied carbon emissions related to the materials added in each renovation package.

Figures 4–6 show the comparison between calculations concerning carbon emissions, NRPE and TPE for the six case studies. Results are shown for the three renovation measures (V1, V2 and V3). In the legends, when alternative energy sources were considered for the same renovation measure, this is indicated in the abbreviation placed after the measure denomination.

Results show that the consideration of embodied energy and embodied carbon emissions does not affect the cost-effectiveness of solutions or the ranking of renovation packages for the investigated indicators, although, as expected, there is a considerable increase in the indicators when the embodied values are considered. There is, however, a verified influence of the consideration of embodied energy and carbon emissions in the potential achievable reduction provided by the implementation of the renovation measures. In that context, in the case studies where all renovation packages are cost-effective, such as in the cases of Austria, Spain and Portugal, including embodied energy and carbon emissions in the calculations provides a decrease in the achievable reduction. For Austria, this means that there is an impact in reductions of 4 to 11% for all indicators. Additionally, results also suggest that the renovation packages with lower primary energy associated to them are the ones presenting higher carbon emissions. The chosen/implemented renovation (V3) is still the renovation package with lower total primary energy and lower carbon emissions associated to it.

In Portugal, there is a decrease in reductions of 2 to 15% and of 2 to 5% for the Spanish case study, considering all the indicators.

For the building in Czech Republic—the only non-residential building—the majority of the solutions are cost effective in all indicators, and the inclusion of the embodied energy and carbon emissions in the calculations has the effect of decreasing reductions by about 5 to 12%. In the Swedish case study, there are a smaller number of measures achieving both cost effectiveness and reduction in carbon emissions, NRPE and TPE. This case study is already served by district heating, a condition sought to introduce a bias in results when fossil fuel alternatives are calculated. This being so, in cost effective renovation packages, there is a decrease of 15 to 32% for NRPE, 8 to 15% for TPE and 9 to 19% for carbon emissions.

For the building located in Denmark, there are no cost effective measures. In fact, the reference case is the one presenting the lowest global costs. However, the effect of considering embodied energy and carbon emissions is also visible in a decrease of the achievable reduction of 3 to 6% for the carbon emissions and 14 to 28% for NRPE and TPE.

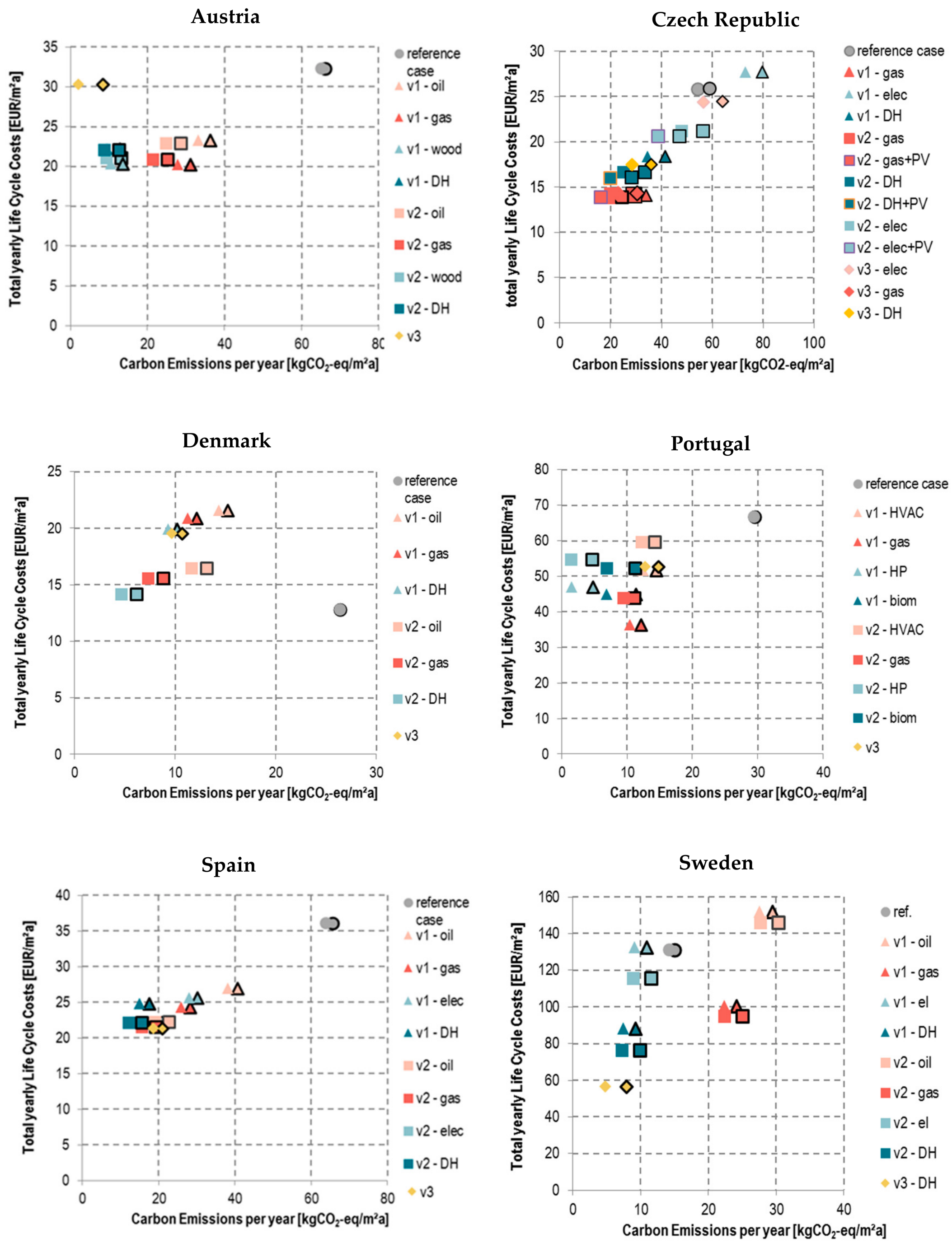

Figure 4. Comparison of calculations for carbon emissions for the six case studies, without including embodied carbon emissions and with embodied carbon emissions (marked with a black outline) for the different renovation packages.

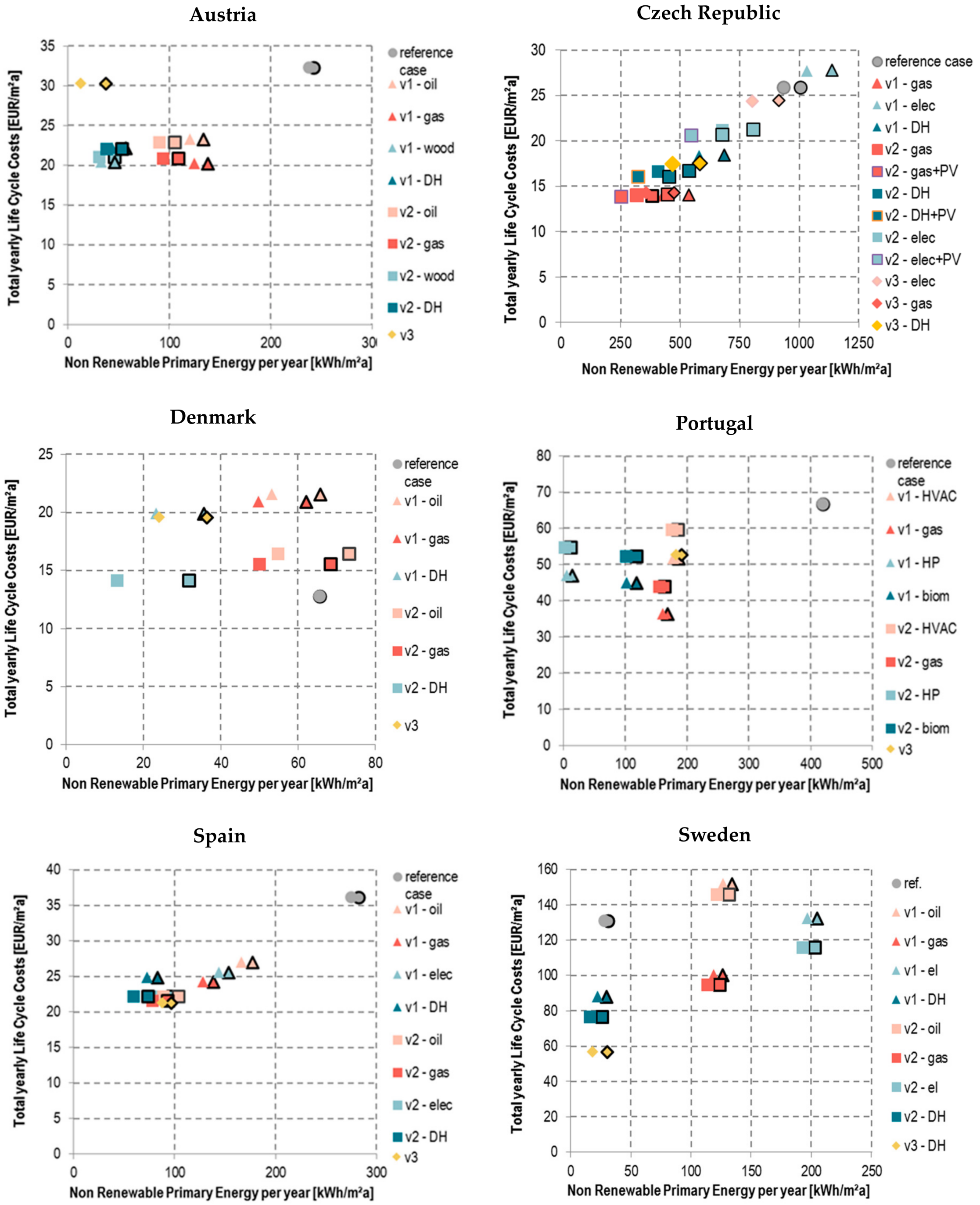

Figure 5. Comparison of calculations for non-renewable primary energy for the six case studies, without including embodied primary energy and with embodied primary energy (marked with a black outline) for the different renovation packages.

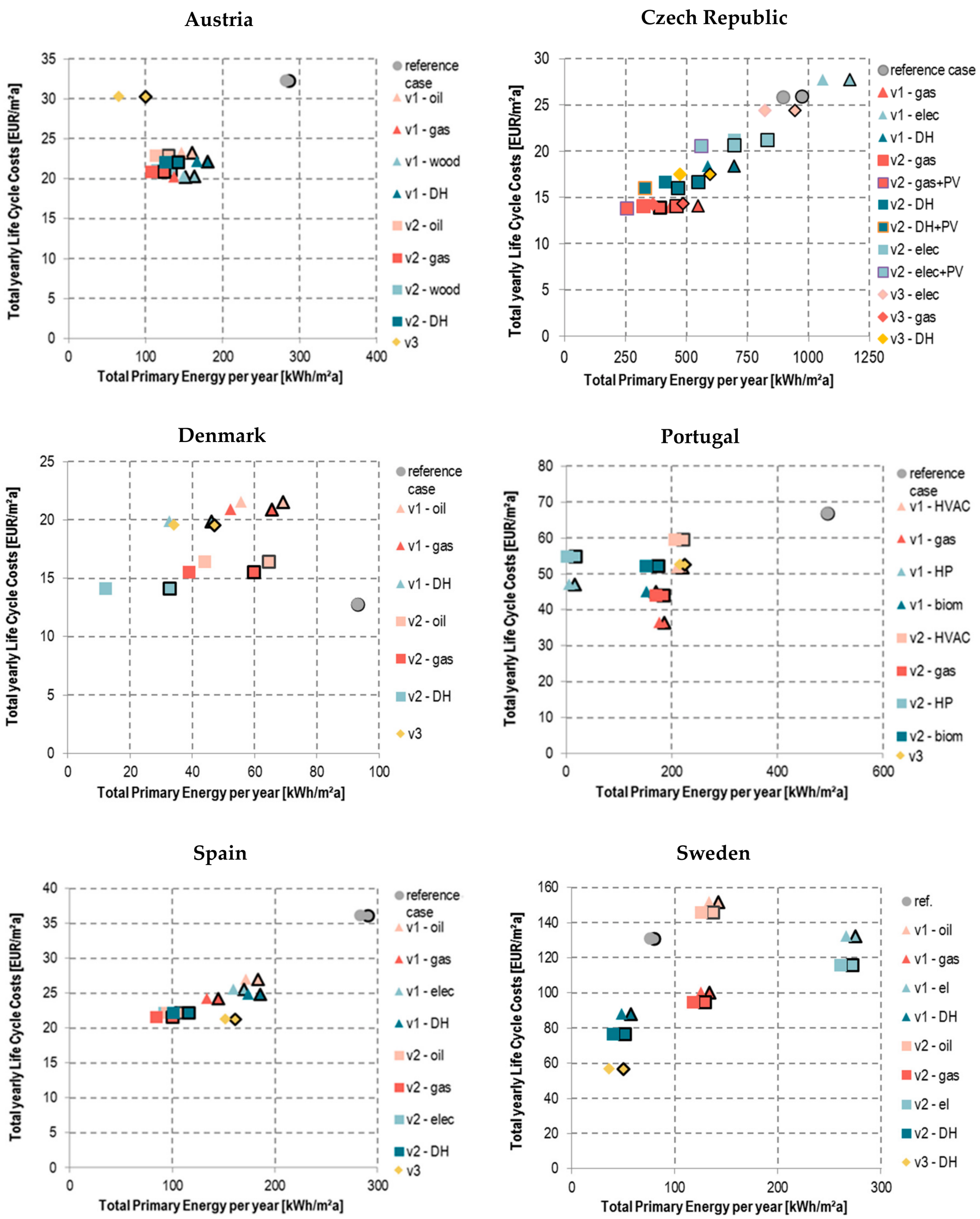

Figure 6. Comparison of calculations for total primary energy for the six case studies, without including embodied primary energy and with embodied primary energy (marked with a black outline) for the different renovation packages.

5. Conclusions

Under the scope of the methodology defined in the Annex 56 project, six case studies were analyzed. The methodology uses a life cycle costs approach to define the cost-effectiveness of renovation actions aiming towards nearly zero energy buildings. In addition, a LCA analysis was promoted in order to understand the potential contribution of considering in the calculations the embodied primary energy and carbon emissions associated to the materials used in the renovation process to the cost effectiveness of the renovation measures tested in the six case studies from different regions in Europe.

After the analysis using the Annex 56 methodology, and despite the different climate conditions, the different building designs and the different renovation measures, it was possible to establish a pattern of behaviour related to the impact of considering the embodied energy and embodied carbon emissions in the evaluation of the cost-effectiveness of the renovation processes. The analyzed indicators do not affect the results obtained without considering the embodied values in terms of the cost effectiveness of the renovation packages. However, a significant decreasing effect of achievable reduction was verified in terms of carbons emissions, NRPE and TPE when the embodied energy and carbon emissions were included in calculations. In addition, results also suggest that when a significant share of renewables is proposed, the embodied component increases and becomes more noticeable. In this sense, it can be stated that when the target is nZEBs, the embodied component is more relevant in the final results. When the target is the lowest cost, the results from the analysis seem to suggest that embodied energy does not play an important role in influencing the results.

Author Contributions: Supervision: M.A.; conceptualization: M.F. and R.B.; writing of the original draft: R.B. and M.F.

Funding: This research received no external funding.

Acknowledgments: The authors would like to thank and acknowledge the six case studies' authors: David Venus, Karl Höfler, Julia Maydl (AT) Jirí Sedlák, Petr Jelínek, Karel Struhala (CZ), Ove Christen Mørck, Iben Østergaard, Kirsten Engelund Thomsen, Jørgen Rose, Søren Østergaard Jensen (DK), Manuela Almeida, Marco Ferreira, Nelson Brito (PT), Ana Sánchez-Ostiz, Silvia Domingo-Irigoyen (ES), Åke Blomsterberg, Rikard Nilsson (SE).

Conflicts of Interest: The authors declare no conflict of interest.

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