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Net-Zero Carbon Emissions Residential Buildings in the Island of Crete, Greece. Are They Feasible?

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Abstract

The necessity to mitigate climate change requires the sharp reduction of carbon emissions in all sectors of human activities. Buildings have a share at around 40% in total energy consumption and emit more than the one third of the global carbon emissions. The feasibility of realizing net-zero emissions residential buildings in Crete, Greece has been investigated focusing on the energy renovation of a grid-connected old residential building with low energy efficiency. The possibility of replacing the conventional energy sources and fuels with locally available renewable energies for heat, cooling and electricity generation has been examined. Various scenarios regarding the energy renovation and the increase of the energy efficiency have been studied. The possibilities of offsetting its embodied energy and generating on-site the required solar electricity for re-charging the batteries of the electric cars of the residents have been also examined. Our results indicate that the use of solar energy, solid biomass and low enthalpy environmental heat, instead of fossil fuels, can eliminate all the life-cycle carbon emissions of the residential building generating additionally the electricity required in the electric cars of the building's occupants. After the energy renovation the grid-connected old residential building will become a net-zero emissions, positive energy and probably zero energy cost building. The installation cost of the required renewable energy systems in the energy renovation is not prohibitive. Our results indicate that old residential buildings in Crete can be de-carbonized using the abundant local renewable energy sources while their energy renovation is economically affordable.

Keywords**:** buildings; carbon emissions; Crete-Greece; electric cars; embodied energy; energy efficiency; operational energy; renewable energies**.**

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1. Introduction

Buildings consume around 40% of the total energy use in Europe while they emit almost 40% of the greenhouse gas (GHG) emissions. The necessity to mitigate climate change which causes many catastrophes in developed and in developing countries requires the sharp decrease of GHG emissions and the replacement of fossil fuels with carbon-free energy sources. The reduction of energy consumption in new buildings and the energy renovation of the existing buildings to become nearly zero energy buildings (NZEB) is obligatory in European Union (EU). In order to achieve the EU targets for net-zero GHG emissions by 2050 the new building regulations aim to fully de-carbonize the building stock in Europe in the coming decades. This can be achieved with the sharp decrease of their energy consumption and the use of low- or zero-carbon energy sources including renewable energies (RE) [1,2,3]. During the last decades a lot of research has been published regarding energy consumption and carbon emissions in residential buildings (RBs) worldwide. Many studies regarding NZEBs have been also implemented [4,5,6]. The energy saving methods and techniques in residential buildings and the energy sources and fuels which are used in them have been analyzed. The integration of solar photovoltaic (solar-PV) systems with electric batteries (EB) in grid-connected residential buildings has been also investigated in the last decade [7,8,9].The energy renovation of the existing old building stock to become carbon neutral and the construction of new zero emission buildings (ZEBs) have several dimensions related to the legal framework, the environmental and climate impacts, the required energy technologies as well as economic and financial aspects [10], [11]. Existing old buildings constructed with old building codes having poor energy performance could be energy renovated covering all their energy requirements with locally available REs eliminating all their carbon emissions. Many RE technologies are currently mature, reliable and cost-effective. Consequently, they can be used in energy renovation of old residential buildings achieving their total de-carbonization [12].

The aims of the current study are:

a) *To investigate the possibility of energy renovation of old residential buildings in the island of Crete, Greece in order to become net- zero emission buildings,*
b) *To investigate which green energy technologies can be used in de-carbonization,*
c) *To investigate if an energy renovated grid-connected old residential building can zero its net carbon emissions related with both the embodied and operational energy.*

The text is structured as follows: After the literature review the energy consumption in RBs, their embodied energy (EE) and their operational energy (OE) are stated. Next, the integration of solar-PV systems with EBs and the use of renewable energies in residential buildings are mentioned. In the following sections the energy renovation of old residential buildings and the concept of ZEBs are presented. After that a case study of a RB located in Crete, Greece which is renovated to become ZEB is presented while the text ends with the discussion of the findings, the conclusions drawn and the citation of the literature used. The current work fills the existing gap regarding the feasibility of creating ZEBs in Crete, Greece taking into account the lack of similar studies. It concerns the total de-carbonization of existing RBs comprising EE, OE and the energy demand for residents' transportation. The research could be useful to engineers, architects, construction and energy companies, policy makers as well as the local authorities who are involved in the clean energy transition of several sectors in the island of Crete.

2. Literature survey

The literature survey is separated in three sections including: a) energy renovation of old RBs, b) integration of solar-PVs with EBs in RBs, and c) carbon emissions in RBs.

2.1. Energy renovation of old residential buildings

The development of net-zero primary energy and GHG emissions RBs in Mediterranean climate has been studied [13]. The authors stated that the energy consumption in buildings represents around 30-40% of the total energy use and the corresponding carbon emissions globally. They also mentioned that net-zero energy buildings do not take into account the EE but only their OE. The authors tried to evaluate the feasibility of achieving net-zero life cycle primary energy and GHG emissions buildings. Their results indicated that an apartment with covered area at 154 m^2 with four occupants equipped with a solar-PV system at 6.5 KW_p, a solar hot water system, low EE and using only electricity can achieve the abovementioned target. The development of NZEBs worldwide has been reviewed [4]. The authors have studied three main factors affecting the development of NZEBs. These include: a) the energy infrastructure comprising electric grids, district heating/cooling networks and energy storage, b) several renewable energy sources and technologies comprising solar energy, wind energy, biomass and micro-generation, and c) energy efficiency measures including insulation of the building envelope, efficient heat, ventilation and air-conditioning (HVAC) systems et cetera. Various myths and facts related to zero energy and ZEBs in Hong Kong have been examined [14]. The author stated that the proper use of well-known energy technologies and the changing behavior of the occupants are both important in achieving NZEBs and ZEBs. He also mentioned that energy self-sufficiency in buildings can be achieved while both NZEBs and ZEBs can become economically and socially acceptable in Hong-Kong. The role of behavioral change in reducing energy consumption and carbon emissions in RBs in several countries using meta-analysis has been studied [5]. The authors stated that both monetary and non-monetary incentives can reduce the energy consumption in households while monetary incentives have a more profound effect. They also mentioned that upgrading the heating system and other equipment in RBs was more effective in reducing carbon emissions compared to behavioral changes of the residents. The energy consumption and the carbon emissions of NZEBs in different climate zones in China have been studied [6]. The authors studied a typical RB in Yangtze River trying to identify the key factors influencing its energy consumption and the carbon emissions. They stated that the use of solar-thermal energy, solar-PV energy and ground source heat pumps (GSHPs) can result in a 61.76% energy saving and a 71% renewable energy utilization rate. They also mentioned that the heat transfer coefficient in the walls and the roof as well as the ventilation rate significantly affect the energy consumption and the carbon emissions in the building. The performance of a zero-energy building in Kyoto, Japan has been analyzed [15]. The authors studied five performance indicators in zero-energy buildings related, a) to energy security, (three), b) to environment (one), and c) to economy (one). These five indicators include: a) On-site electricity generation by REs, b) Energy self-sufficiency, c) Reduced energy loss due to electricity conversion, d) De-carbonization of the electricity generation, and e) Reduction in the electricity cost. The integration of solar-PV systems, solar-thermal systems and heat pumps (HPs) in net-zero energy buildings in Spain has been studied [12]. The authors stated that it is possible to cover almost the whole energy demand including domestic hot water (DHW) production and electric loads in buildings with the integration of solar energy systems and small-size EBs. They also mentioned that the critical factor hindering the promotion of these energy systems in buildings is the high cost of batteries. The definitions of zero-energy buildings have been reviewed [16]. The authors stated that although the concept of zero-energy building is simple there is not a commonly agreed global definition. They classified the existing definitions of zero-energy buildings as follows: a) zero energy, b) zero carbon, c) zero exergy, and d) zero cost. Additionally, they classified them as off-grid and on-grid. On-grid zero-energy buildings were further classified as: a) nearly-zero energy, b) net-zero energy, and c) plus energy. The implementation of the concept of NZEBs in Mediterranean region has been studied [11]. The authors stated that the aggregated use of solar-PV energy, geothermal energy and energy storage systems in a multi-family building allow the self-production and self-consumption of energy. They also stated that the proposed NZEB scheme is a sustainable energy solution in Mediterranean region while the use of energy storage in EBs will enhance the stability and the reliability of the grid. The EE in NZEBs has been reviewed [17]. The authors stated that the share of the EE in low-energy buildings could reach up to 57% or even up to 83% when renewable energies are used for electricity generation. They also mentioned that in NZEBs the share of EE could reach up to 100% of the life cycle energy. The reduction of the life cycle EE in RBs has been studied [18]. The author stated that the increase in their service life and in the life of their constituent materials is important for reducing their life cycle EE. The EE and the OE in the framework of NZEBs with reference two RBs in Italy have been assessed [19]. The authors stated that the share of their EE to their life cycle energy is in the range of 25% to 34%. The EE and OE in NZEBs have been studied [20]. The authors calculated the EE and the OE in an office building located in Tourin, Italy. They estimated the share of the EE and the OE in a conventional building and in a NZEB. They stated that the share of the EE to life cycle energy in the conventional building was in the range of 25% to 39% while in the NZEB in the range of 57% to 71% concluding that the share of EE to life cycle energy in NZEBs is significantly higher compared to conventional buildings. Energy renovation of old RBs constructed with old building codes having a poor energy performance is necessary for many reasons. It is going to reduce the energy-related carbon emissions which is important for climate change mitigation. It is going to reduce the energy bills of households protecting them from uncertainties in future energy prices. It is going to increase the quality of life of the residents improving the buildings' heating and cooling characteristics. It is going also to increase their renting and selling price of the buildings.

2.2.Integration of solar photovoltaics with electric batteries in residential buildings

The use of small size solar-PV systems coupled with batteries in households and their impact on the peak shaving potential of the electric grid at district level in the Netherlands has been studied [8]. The authors analyzed the behavior of these systems in 79 households in Amersfoort, Netherlands with average nominal power per household at 2.4 KW_p and average optimal capacity of batteries per household at 3.4 KWh. They estimated that the peak shaving potential, due to the installation of these small-size integrated solar-PV/battery systems, was at 5.7%. The solar-PV/battery systems in different household profiles in Zurich, Switzerland have been assessed [21]. The authors studied 4,190 households considering an optimal system configuration with mean solar-PV power at 4.4 KW_p and mean battery capacity at 9.6 KWh. Assuming the unit cost of the solar-PV system at 2,000 €/KW_p and the cost of the battery at 1,000 €/KWh they estimated that, in the case of the solar-PV system without electricity storage, approximately 40% of the households had positive net present value (NPV) but only 0.1% for the integrated solar-PV/battery systems. The profitability of residential solar-PV systems coupled with lithium-ion batteries in USA has been analyzed [9]. The authors stated that with appropriate sizing integrated solar-PV/battery systems can be more affordable than solar-PVs without storage. They studied an integrated system with solar-PV power at 5 KW_p and battery's capacity at 7 KWh. The authors mentioned that the system performance and its economics varies geographically across the 50 states while, assuming a 30% investment tax credit, the calculated levelized cost of electricity (LCOE) varies between 0.1 \$/KWh to 0.17 \$/KWh. A solar-PV system with battery storage installed in a grid-connected residential building in China has been studied [22]. The authors stated that the battery storage system was beneficial to the electric grid reducing the peak load and the voltage swings. They also mentioned that the abovementioned system had negative NPV and it was not profitable in the Chinese context. A solar photovoltaic system with battery storage in a grid connected house with energy sharing located in south Australia has been studied [7]. The authors stated that the energy sharing between the two houses was mutually beneficial. They also mentioned that the size of the photovoltaic system was at 10 KW_p and the battery's capacity at 7 KWh. The cost of electricity in the first house was reduced by 7.6% while in the second house at 9.7% due to energy sharing between them. The configuration effectiveness of integrated solar-PV and battery systems in RBs in Australia has been studied [23]. The authors stated that the creation of a shared micro-grid among three apartment buildings with integrated solar-PV/battery systems increases their self-sufficiency more than 60% resulting also in less usage of grid electricity. The self-consumption of solar-PV electricity in buildings has been reviewed [24]. The authors stated that there are two methods which can increase the self-consumption of solar-PV electricity in buildings: a) the energy storage, and b) the load management. Regarding the energy storage the battery's capacity should be at around 0.5-1 KWh per installed KW_p solar power. They also mentioned that the relative self-consumption can be increased by 13%-24% with electricity storage and by 2%-15% with demand-side management. The self-consumption and the self-sufficiency in residential solar-PV systems have been studied [25]. The authors investigated the use of a HP for heating, cooling and DHW production combined with water storage tanks and EBs in an Australian house. They stated that the system could increase the self-consumption by 41.96% and the self-sufficiency by 86.34%. The storage of solar-PV electricity in RBs in Finland has been studied [26]. The authors stated that both the size and the cost of integrated solar-PV/battery systems installed in RBs should be optimized. The economic viability of integrating solar-PV systems with EBs in RBs has been reviewed [27]. The authors stated that currently it remains unclear if battery storage is profitable in residential solar-PV systems without financial support. The authors stated that battery storage is profitable for small-scale residential applications. They also mentioned that if households will not be allowed to sell excess electricity in the wholesale market the profitability of electricity storage in residential solar-PV systems would be high. The optimal sizing of battery storage in solar-PV systems installed in RBs has been studied [28]. The authors have analyzed 175 buildings in Germany stating that, when the optimization of the grid operation is required, the optimal size of battery's capacity should be at 2.28 KWh per KW_p of installed solar-PV. They also mentioned that for optimizing the system profitability the optimal battery's capacity should be at 0.54 KWh per KW_p of installed solar-PV. The recent developments of solar-PVs integrated with battery storage systems in several countries have been studied [29]. The authors stated that self-consumption is the key factor for the development of incentivization policies while the feed-in tariff scheme is still the most effective scheme for the promotion of integrated solar-PV/battery systems. A stand-alone solar-PV vehicle charging station has been studied [30]. The authors stated that utilization of stand-alone charging stations facilitates the stability of the electric grid. They also mentioned that the use of storage batteries in charging stations compensates the solar electricity variations due to solar insolation disturbances. The solar-powered charging stations of electric vehicles (EVs) have been studied [31]. The authors studied the feasibility of a solar-PV charging station for EVs installed in a car park stating that the charging rate in several commercial car models varies between 3.3 KW to 10 KW. They also calculated the size of the solar-PV panels, the median cars' energy demand, the median charging time and other parameters concluding that the development of solar-PV electric chargers in car parks is a challenging opportunity nowadays. The installation cost of EBs in RBs is still high and it is subsidized by public funds. However, technology innovations and advances are going to reduce their cost and it is foreseen that their use will be propagated soon. Additionally, the increase in small scale electricity storage capacity is going to improve the grid characteristics and to facilitate the higher penetration of REs in the energy system.

2.3 Carbon emissions in residential buildings

The possibility of achieving net-zero carbon emissions in construction supply chains focusing on RBs has been studied [32]. The authors compared different building designs and investigated the use of available low-carbon technologies and carbon dioxide (CO_2) abatement measures. They stated that GHG emissions can be reduced by up to 40% with the current available technologies and practices while reductions up to 80% can be achieved in 2030 and up to 93% in 2045. The life cycle carbon emissions in high-rise residential buildings focusing on Hong Kong have been evaluated [33]. The authors stated that the life cycle GHG emissions in a RB located in a densely populated area in Hong Kong was at 4,980 $kgCO_2/m^2$. They also mentioned that over 86% of the emissions resulted during the operation of the building including its renovation. The carbon emissions in RBs have been estimated [34]. The authors stated that according to several studies over 90% of the carbon emissions are generated during the operational phase of the building. They highlighted the importance of emissions during the construction phase for two reasons. Firstly, the improvement of energy efficiency in buildings increases the relative share of EE. Secondly, the temporal allocation of carbon emissions increases the importance of the construction-related emissions which are occurring in the initial stage of the building's life. The creation of net-zero emission residential buildings due to life cycle energy use in Mediterranean region has been investigated [1]. The possibility of re-charging the batteries of the EVs of the residents has been also taken into account. The author studied a grid-connected RB with covered area at 120 m^2 using a solar thermal system for DHW production, a solar-PV system and a GSHP. He stated that the size of the solar-PV system was evaluated in the range of 5.98 KW_p to 12.38 KW_p while the installation cost of the solar-PV system varies between 7,181€ and 14,861€. He also mentioned that the annual CO_2 savings vary between 74 $kgCO_2/m^2$ to 134 $kgCO_2/m^2$. The difficulties in modelling carbon emissions in public RBs in Hong Kong have been examined [35]. The authors stated that the existing models have some shortcomings which should be overcome. They have also indicated how carbon emissions should be calculated in RBs in Hong Kong. The development of net-zero emission residential buildings due to OE use in Crete, Greece has been studied [36]. The author stated that solar thermal energy, solar photovoltaic energy, solid biomass and low-enthalpy environmental heat can be used for the creation of RBs with net-zero carbon emissions in Crete. He also estimated that the installation cost of the necessary renewable energy systems in a RB for zeroing the net carbon footprint due to OE use does not exceed 10% to 12% of its construction cost. The trade-offs between CO_2 emissions and primary energy use in buildings have been studied [37]. The authors stated that the increasing share of REs in the total energy mix in houses results in lower CO_2 emissions. They also mentioned that the same share of REs in the energy mix in buildings can result in different CO_2 emissions. A low-carbon roadmap for the residential sector in China has been studied [38]. The authors estimated that the peak in carbon emissions in the residential sector in China will be in 2037. They also stated that the future benchmark in carbon emissions in the residential sector in the country should be at 0.703 billion tons. The contribution of NZEBs in achieving carbon neutrality by 2060 has been examined [39]. The authors stated that the upgrading of the energy standards in the building sector to achieve NZEBs will contribute at 50.1% in achieving carbon neutrality in China by 2060 while the generation of zero-carbon electricity will have a share at 49.9%. The life-cycle approach to optimize the carbon footprint due to EE and OE use as well as the energy cost in a RB in Finland has been studied [40]. The authors, using simulation-based optimization, investigated different options in the house regarding the insulation of the envelope and the use of REs stating that the building's heating was an important parameter. They also mentioned that the share of the embodied carbon to life-cycle carbon varies in the range of 28% to 39%. The definition of ZEBs in Australia has been reviewed [2]. The authors have reviewed the definition of low, zero and positive emissions buildings. They have separated their life cycle emissions in five stages as follows: a) before use (embodied emissions), b) during operation (operational and renovation emissions), and c) after use (demolition emissions). They stated that life cycle carbon emissions include all the abovementioned emissions. They also mentioned that ZEBs should meet specific standards for energy efficiency and on-site energy generation while they should be monitored in GHG emissions as $kgCO_2$-e/m^2 year. The link between low-carbon reduction strategies and their performance in RBs in Canada has been examined [41]. The authors studied four strategies including: a) use of low-carbon materials, b) minimization of materials' use, c) reuse and recycle of materials, and d) adoption of local benign energy sources. They stated that the pre-fabrication approach in buildings reduces their carbon footprint while the adoption of low-carbon strategies is beneficial to climate change mitigation. The low carbon refurbishment solutions for RBs in Hong Kong have been studied [42]. The authors stated that different sustainable refurbishment options have different performance in emissions' reduction which varies significantly. They identified 39 suitable sustainable refurbishment options out of 88 existing solutions for subtropical cities like Hong Kong. The carbon mitigation in households during the "Post Paris era" in China using decomposition analysis has been assessed [43]. The authors identified three economic indicators which contribute in decreasing carbon intensity in RBs. These indicators are: a) housing purchasing power, b) housing price-to-income ratio, and c) population size per household. Additionally, they stated that emissions in electricity generation were affecting indirectly the carbon emissions in households. The zero-carbon refurbishment of buildings has been studied [3]. The authors have categorized several technologies which can be used in buildings' refurbishment to minimize their carbon emissions. These include better insulation of the envelope, low energy lighting, heating, ventilation and micro-generation. The feasibility of reducing the GHG emissions in RBs has been studied [44]. The authors examined more than 100 homes in Denver, USA calculating the cost of energy renovation in order to comply with the new energy codes. They stated that the energy renovation of existing RBs to become NZEBs is not cost-effective for the owner while governmental support is required to facilitate their clean energy transition. The factors influencing the carbon emissions in RBs in Heuan province, China have been investigated [45]. The authors stated that carbon emissions in RBs increased from 2010 to 2020 albeit the growth rate was decelerating. They also mentioned that the main factor affecting carbon emissions was the income of the household. They predicted that during the period 2020-2050 the carbon emissions in RBs in this province will exhibit an inverted U-shaped trend while the peak year will be in 2036. The concept of net carbon buildings has been mentioned by the World Green Building Council [46]. A net carbon building should first reduce its energy demand and then all its remaining needs should be covered by renewable energies. EU has defined a ZEB as a building with very high energy performance while its low energy demand should be fully covered by renewable energies without on-site carbon emissions by fossil fuels [47]. World Economic Forum has identified four crucial trends for achieving ZEBs [48]. These include: de-carbonization, electrification, high energy efficiency and digitalization. The development of NZEBs in Europe has been assessed [10]. The authors stated that decarbonization is crucial to achieve the future energy and climate goals. They have overviewed the most commonly implemented technologies in NZEBs mentioning that photovoltaics will be probably the pillar to de-carbonize our power supply in the next decades. Clarifications regarding the revision of the current EPBD have been provided by EU, 2021 [49]. The revised directive aims to de-carbonize the EU building sector by 2050. Fossil fuels are not going to be used for heating after 2040 while the direct emissions of buildings should be decreased by around 80%-89% by this year. The revised EPBD includes a definition for ZEBs, for deep renovation and for new performance metrics including final energy consumption and life-cycle carbon emissions. The recommended EU directive 2019/786 on building renovation, 2019 has introduced some new concepts regarding the de-carbonization of the building stock in EU countries [50]. The new concepts comprise the cost-effective renovation of buildings, the deep renovation with more than 60% improvements in energy efficiency, the use of smart technologies in buildings and the renovation priority to the worst-performing segments of the national building stock. The current EPBD III is going to be updated soon, 2023 [51]. The new EPBD IV is going to promote the achievement of zero-emission and fully de-carbonized building stock by 2050. According to the new EPBD, ZEBs will become the standard norm as of 2028 as opposed to the current NZEBs norm. Additionally, the new EPBD is going to introduce minimum energy performance standards supporting financially the required energy renovation in buildings. For achieving the ambitious EU target for eliminating all the net carbon emissions by 2050 the elimination of emissions in buildings is going soon to be obligatory. There are plenty reliable, mature, well-known and cost-effective green energy technologies which can be used in buildings. Although the installation cost of zero-carbon energy technologies in buildings is currently high several financial mechanisms are going to be developed and used assisting the implementation of clean energy transition in households.

3. Energy consumption in residential buildings

Residential buildings use energy for covering the needs of the occupants in space heating and cooling, DHW production, lighting and operation of several electric appliances. Additionally, if the residents of the building use EVs they might use electricity for re-charging their batteries at home. The energy consumed during the operation of a building is called OE. Additionally, energy is contained in the constituent materials while it is also used during the construction of the building, its renovation and during its demolition in the end of its life cycle. All this energy is called EE. The sum of the EE and the OE is called life-cycle energy of the building. The OE consumption in RBs depends on many parameters including the type of building’s construction, the local climate, the behavior of the occupants et cetera. The carbon emissions due to OE use in RBs depend also on their specific energy consumption and on the energy sources and fuels used. Conventional RBs constructed with the old building codes before the introduction of the concept of NZEBs, in the beginning of the 21st century, have low energy efficiency and significantly higher energy consumption and carbon emissions than NZEBs.

4. Embodied energy in residential buildings

Several studies have been implemented in conventional RBs investigating the share of EE and OE in their life-cycle energy. The results indicated that the share of EE in the life cycle energy varies in the range of 10% to 20% while the rest corresponds to OE [34], [33]. The share of EE is higher in NZEBs, compared to conventional old residential buildings, due to lower OE consumption. The share of EE in NZEBs has been calculated in the range of 28% to 39% [40] of 57% to 83% [17] and of 25% to 34% [19]. The share of carbon emissions in their embodied and operational phase follows a similar pattern although it depends on the type of energy and fuels used in the operational phase of the building. The embodied carbon emissions in RBs depend on carbon emissions related a) with the buildings' construction materials and b) the emissions related with the energy use during their construction, refurbishments and demolition. When the energy required in NZEBs is provided by REs with zero carbon footprint then the share of their EE in the life cycle energy use could reach up to 100%. The total elimination of carbon emissions in RBs requires, apart from the elimination of the emissions related to their OE, the elimination of the emissions related to its EE. This requires the use of low carbon buildings construction materials, construction of positive energy residential buildings and/or the use of carbon offsetting mechanisms.

5. Operational energy in residential buildings

The energy consumed during the operation of a residential building is called OE. It includes the energy used in several sectors including: a) space heating and cooling, b) production of DHW, c) lighting, and d) operation of various electric appliances and equipment. The OE in RBs depends on many factors including the local climate, the type of the building construction, the appliances and the lighting system used, the efficiency of the heating and cooling system, the behavior of the occupants et cetera. The main energy sources and fuels used in typical RBs comprise: grid electricity, natural gas, heating oil, district heating and cooling systems, solid biomass, low enthalpy environmental and underground heat with HPs, solar energy with on-site or off-site solar thermal or solar-PV systems, small wind turbines, green energy provided by an external provider or an energy cooperative et cetera. The operational energy use in a typical conventional residential building located in Crete, Greece is presented in table 1. The benchmark of energy performance in NZEBs in Mediterranean area's climate zone is presented in table 2.

Table 1: Operational energy use in a typical conventional residential building located in Crete, Greece

Sector	Energy consumption (KWh/m^2 year)	%, energy use
Space heating	107.1	63
Hot water production	15.3	9
Lighting	20.4	12
Operation of various electric appliances including space cooling	27.2	16
Total	170	100

Source: [36]

Table 2: Benchmark of energy performance in NZEBs in Mediterranean area's climate zone

Energy consumption	KWh/m^2 year
Total primary energy use	85-100
Net primary energy use (excluding on-site renewable energies)	40-55

Source: [10]

6. Electricity storage in residential buildings

Electricity storage in stand-alone residential buildings equipped with solar-PV systems is necessary. Grid-connected RBs with solar-PV installations can store solar electricity in EBs preferably in lithium-ion batteries. Electricity storage increases their self-sufficiency and provides electricity in cases of undesired emergencies, grid failure and climate disasters. Therefore, it increases the energy security of the residents. Electricity storage in buildings has positive impacts on the electric grid resulting in shaving its peak potential and reducing the voltage swings [8,22]. The profitability of installing solar-PV systems without electricity storage in RBs is already proven with many applications worldwide. However, several studies have indicated that the integration of EBs in residential solar-PV systems is not profitable for the households without financial support or financial subsidies [27,21]. The optimal battery capacity has been found at 0.5 KWh/KW$_p$ - 1.0 KWh/KW$_p$ [28] and at 1 KWh/KW$_p$ - 2 KWh/KW$_p$ [8]. It should be also taken into account that small-scale electricity storage in households can assist the higher penetration of REs in the energy system which is necessary for climate change mitigation. It can also help to achieve the European target for 2050 regarding the de-carbonization of the building stock [50].

7. Use of renewable energies in residential buildings

Depending on their availability several RE sources are used in RBs covering their demand in heat, cooling and electricity. Solar energy can be used for heat and electricity generation, wind energy for electricity generation, solid biomass for heat generation and high efficiency HPs for heat and cooling production. The electricity required for the operation of HPs can be zero-carbon solar electricity. These green energy technologies are currently mature, reliable, well-known and cost-effective. The most commonly used renewable energies in NZEBs are presented in table 3.

Table 3: Most commonly used renewable energy technologies in NZEBs

Renewable Energy Technology	Use, %
Solar-PV	64.7%
Low-enthalpy geothermal energy with HP	27.5%
Solar thermal	17.6%
Biomass	15.7%
Wind energy	5.9%
Ambient heat with HP	3.9%

Source: [10]

Several renewable energy technologies are already used in grid-connected RBs in Crete. The solar irradiance in the island is high while large quantities of solid biomass are available due to the extensive cultivation of the olive tree in the island. Green electricity can be also purchased from local energy cooperatives. Solar-PV panels, flat-plate solar thermal collectors, biomass burning systems and HPs can be installed within the residential building generating heat, cooling and electricity. The zero-carbon energy technologies which can be used in residential buildings in Crete are presented in table 4.

Table 4: Zero-carbon energy technologies which can be used in residential buildings in Crete

Energy source	Energy technology	Generated energy
Solar energy	Solar photovoltaic panels	Electricity
Solar energy	Flat-plate solar thermal collectors	DHW
Solid biomass based on olive tree residues and by-products	Biomass burning systems	Heat, DHW
Ambient heat, low-enthalpy geothermal energy, electricity	Heat pumps	Heat, cooling, DHW
Green electricity purchase from energy providers/cooperatives		Electricity

Source: Own estimations

8. Energy renovation in residential buildings

Old RBs which have been constructed with the old building codes have low energy efficiency and high emissions of GHGs. The European and global efforts for climate change mitigation in the “Post Paris Era” require the sharp decrease of energy consumption and carbon emissions in buildings. The current EU regulations promote the creation of NZEBs as well as the energy renovation of old RBs to become NZEBs. Soon the revision of the European EPBD is going to promote the ZEBs. These buildings should have very low energy consumption and net-zero carbon emissions covering all their energy needs with zero-carbon energy sources. Various smart and efficient energy saving technologies should be used decreasing their energy consumption while the remaining energy demand should be covered preferably with locally available REs. Technology advances allow the use of several REs for heat, cooling and electricity generation while their technologies are mature, reliable and cost-efficient. The most commonly REs used in NZEBs are presented in table 5 while the main barriers for their energy renovation are presented in table 6.

Table 5: Main renewable energy generation options for NZEBs

	Renewable energies used in NZEBs
1.	Renewable energy use within the building (solar-PV, solar-thermal, small wind turbines, HPs)
2.	Renewable energy use within the boundary of the building (solar-PV, solar-thermal, small wind turbines, HPs)
3.	Off-site renewable energy to provide energy in the building (biomass, district heating)
4.	Purchase renewable energy generated off-site (private company, energy cooperative)

Source: [10]

Table 6: Barriers for energy renovation of residential buildings

Barrier	Description
Financial	High cost of energy renovation, Lack of own financial resources, Lack of access to bank loans and state subsidies
Regulatory	Lack of appropriate regulatory framework
Technical	Difficulties in using several low carbon energy technologies, High cost of clean energy solutions
Awareness	Lack of understanding the necessity for energy refurbishment
Information	Lack of sufficient information in various aspects of energy renovation
Expertise	Lack of providers' expertise, Lack of skilled technicians

Source: [10]

9. The concept of net-zero emissions residential buildings

A net-zero-emissions RB (on-site) is an energy efficient residential building that generates sufficient CO_2-free energy on-site over a year to supply all expected on-site energy requirements for the residents. The energy demand of the building comprises heat, cooling and electricity (including the electricity required for re-charging the batteries of the EVs of the occupants). The difference between ZEBs and NZEBs is that in NZEBs the energy consumption is low while the zeroing of their carbon emissions is not obligatory. On the contrary, in ZEBs the energy consumption is low while it should be covered by REs in order to zero their net-carbon emissions. Several characteristics of conventional residential buildings, NZEBs and ZEBs are presented in table 7.

Table 7: From conventional buildings to NZEBs and to ZEBs

Type of building	Construction period	Characteristics	Energy efficiency	Energy technologies used	Carbon emissions
Conventional buildings	Until the end of 20th century	The energy consumption and the carbon emissions were not important parameters in the design of the building	Low to moderate	Conventional and renewable energy technologies	Indifferent, often high
NZEBs	Beginning of 21st century	Low energy consumption and low carbon emissions are obligatory	Requirements for high energy efficiency	Mainly low-carbon energy technologies	Low
ZEBs	2025 to 2050	Zeroing the carbon emissions is obligatory	Requirements for very high energy efficiency	Zero-carbon energy technologies	Zero

Source: Own estimations

10. A case study of a ZEB in the island of Crete, Greece

Several old RBs in Crete can be renovated to become ZEBs. An old grid-connected detached house, with covered surface at 150 m^2, located in the suburbs of the city of Chania, western Crete was studied. It is a conventional detached house with four occupants constructed in 1995 with the old building codes while its life expectancy is at around 50 years. The occupants use two EVs with re-chargeable batteries which should be re-charged at home. Each EV travels 8,000 Km/year while its electricity consumption is at 0.15 KWh/Km. The energy losses during batteries' re-charging are 15%. The electricity required for re-charging the batteries of these two EVs is calculated at 2,760 KWh/year or 18.40 KWh/m^2 year. The OE demand of the residential building is at 170 KWh/m^2 year (table 1) while its EE is assumed at 15 % of the life-cycle energy use, at 25.5 KWh/m^2 year. Consequently, the life cycle energy of the building is at 195.5 KWh/m^2 year. The old building will be renovated to become a ZEB which would have net-zero carbon impacts due its life-cycle energy use including the electricity required to re-charge the batteries of two EVs. The building after the energy refurbishment will have the following characteristics:

a) It will be an on-grid ZEB regarding its life-cycle energy use,

b) It will be an energy-plus RB (generating excess green electricity in order to offset the carbon emissions related with its EE). Solar-PVs installed either on-site or off-site of the building will generate annually carbon-free electricity equal with the OE demand, the EE demand and the energy required in the EVs of the residents, and

c) If only solar energy is used in the de-carbonization, the building will be a zero-cost building regarding the energy cost.

Summarizing the conventional RB will become a ZEB, energy plus and zero energy cost building. The following three scenario have been considered:

a) The residential building will not reduce its OE consumption,
b) The residential building will undergo a moderate energy refurbishment reducing its initial energy consumption by 30%,
c) The residential building will undergo a deep energy refurbishment reducing its initial energy consumption by 70%,

In each scenario the OE, the EE, the electricity required for re-charging the batteries of the electric vehicles, the nominal power of solar-PVs generating carbon-free electricity equal with the annual energy demand in the residential building as well as the installation cost of the solar-PVs are calculated and presented in table 8. The total energy consumption of the building comprises the OE, the EE and the energy required for re-charging the batteries of the EVs.

Table 8: Several characteristics of the ZEB located in Crete under the three abovementioned scenarios

Scenario	OE (KWh/m^2y)	EE (KWh/m^2y)	Life-cycle energy (KWh/m^2y)	Energy of EVs (KWh/m^2y)	Total energy consumption (KWh/m^2y)	Total energy consumption (KWh/y)	Nominal power of PV-system (KW_p)	Installation cost of PV-system (€)
Without energy renovation	170	25.5	195.5	18.40	213.9	32,085	21.39	25,668
Moderate energy renovation	119	25.5	144.5	18.40	162.9	24,435	16.29	19,548
Deep energy renovation	51	25.5	76.5	18.40	94.9	14,235	9.49	11.388

Source: Own estimations, Annual electricity generation by solar-PVs in Crete = 1,500 KWh/KW_p, Installation cost of solar-PVs = 1,200 €/KW_p.

All the energy requirements of the abovementioned RB in Crete can be covered with REs including solar energy and locally produced solid biomass. Additional solar-PV electricity can be generated for offsetting its EE. The zero-carbon energy technologies which can be used in RBs located in Crete are presented in table 9.

Table 9: Several zero-carbon technologies which can be used in ZEBs located in Crete

Sector	Energy technology	Zero-carbon energy source
Space heating	a) Biomass burning b) Heat pump	a) Solid biomass b) Ambient heat, geothermal heat, green electricity
Space cooling	a) Heat pump	a) Ambient heat, geothermal heat, green electricity
DHW	a) Flat-plate solar thermal collectors b) Biomass burning c) Heat pump	a) Solar energy b) Solid biomass c) Ambient heat, geothermal heat, green electricity
Lighting	a) Solar-PV panels, green electricity purchase	a) Solar energy
Operation of electric appliances	a) Solar-PV panels, green electricity purchase	a) Solar energy
Offsetting the EE	a) Solar-PV panels, green electricity purchase	a) Solar energy
Re-charging the batteries of EVs	a) Solar-PV panels, green electricity purchase	a) Solar energy
All sectors	a) Buying green electricity from an energy provider or from an energy cooperative	b) Various renewable energies.

Source: Own estimations

11. Discussion

Old RBs in the island of Crete, Greece, constructed with the old building codes, can be renovated to become ZEBs. This can be achieved with replacement of the conventional energy sources and fuels used with locally available REs including solar energy, solid biomass and low enthalpy environmental heat. Use of solar thermal energy for DHW production, solar-PV systems for electricity generation, solid biomass burning for heat production and high-efficiency HPs for heat and cooling production in Crete are mature, reliable and cost-effective technologies. RBs can zero their net carbon emissions due to both EE and OE use becoming positive energy buildings. The required nominal power of a solar-PV system, calculated by *Andre and his colleagues, 2020,* for de-carbonization of an almost similar RB in Mediterranean region, at 6.5 KW_p, is lower than our estimations. Recent advances in several RE technologies have reduced their cost allowing their use in several applications including in RBs. The realization of ZEBs requires the significant decrease of their energy consumption and the use of carbon-free energy sources to cover the remaining energy demand. The use of solid biomass for heat production results in on-site carbon emissions while the use of solar energy and HPs has zero on-site carbon impacts. However, old RBs in Crete can be renovated to become ZEBs with or without increasing their energy efficiency. Therefore, old RBs with low energy efficiency, constructed with the old building codes, can be de-carbonized replacing the conventional energy sources and fuels used with locally available zero-carbon energy sources eliminating all their carbon emissions. Replacement of fossil fuels and grid electricity with renewable energies in RBs owned by energy poor households can improve the energy behavior of the buildings and the quality of their life. Additionally, they can offset their carbon emissions related with their EE generating equal amount of carbon-free solar electricity using solar-PV panels. It should be noted that RBs might not have the necessary available free space to install on-site solar-PV panels and solar thermal collectors to generate carbon-free electricity and DHW. Our study has limitations related to: a) the behavioral change of the buildings' occupants has not been taken into account while it is important for reducing the energy consumption and improving their energy efficiency, and b) only one RB with a specific energy consumption has been studied in order to reach in the conclusions drawn. However more RBs with different specific energy consumption should be studied in order to have more reliable results. The parameter of behavioral change of the buildings' occupants though has not been taken into account in our study. Future research should be focused on the investigation of the economics and the profitability of different RE technologies which can be used in energy renovation of old RBs in Crete transforming them to ZEBs.

12. Conclusions

The new European regulations are going to eliminate the carbon emissions due to energy use in the building sector including in residential buildings. It should be noted that the significant reduction of energy consumption in buildings should be prioritized in order to eliminate their carbon emissions. The feasibility of energy renovation of old, grid-connected, RBs constructed with the old building codes, to become ZEBs, without reducing their initial energy consumption, in the island of Crete, Greece has been investigated. The possibility of achieving zero-emissions impacts due to life cycle energy use has been also examined. The zero-carbon energy sources which can be used for that have been identified. Our findings indicate:

a) Grid-connected old RBs in Crete with low energy efficiency can be renovated to become ZEBs with zero climate impacts due to EE and OE use.
b) The RE sources which can be used replacing the conventional energy sources and fuels include: solar energy, solid biomass and low enthalpy environmental and underground heat. These REs are abundant in the island.
c) The electrification in all sectors in RBs results in zeroing their on-site carbon emissions.
d) These energy technologies which can be used are: a) solar thermal technology, b) solar photovoltaic technology, c) solid biomass burning, and d) high efficiency HPs. These technologies are mature, reliable, cost-effective while they are already used in many applications.
e) Solar-PV systems installed in grid-connected RBs for electricity generation can be integrated with EBs storing part of the solar electricity generated.
f) The solar-PV systems installed in RBs can re-charge the batteries of the EVs used by the residents.
g) An old grid-connected RB with low energy efficiency located in Crete can become ZEB with or without

increasing its initial low energy efficiency.

h) Our case study of an old RB in Crete, with covered surface at 150 m^2 and annual energy consumption at 170 KWh/m^2, which has undergone energy renovation indicates that it can become: a) ZEB due to life cycle energy use, b) energy positive building, and c) zero energy cost building if solid biomass will not be used.

i) The size and the cost of the necessary solar-PV system generating the required electricity in the renovated building depends on the degree of the energy renovation. It varies between 9.49 KW_p to 21.39 KW_p and 11,388 € to 25,668 € correspondingly while in any case the installation cost is affordable for the owner.

j) The installation cost of the abovementioned benign energy technologies in RBs are currently partly subsidized by the government for low-income households.

Our work indicates that the old residential building stock in Crete, Greece can be fully de-carbonized to comply with the national and EU targets for climate change mitigation in the next decades. Our results could be useful to local authorities, policy makers, citizens, architects, engineers, real estate and energy companies, non-governmental organizations et cetera.

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