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Zero-Emission Potential of Single-Family Houses in Croatia

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Abstract

The EPBD 2024 recast sets the deadline for new Zero-Emission Building standards for all new publicly owned buildings to 2028 and to 2030 for all new buildings. In the scope of Life Cycle Assessment stages, all steps resulting in major emissions from buildings must be considered and presented. The research evaluates the life cycle greenhouse gas emissions of a single-family house, focusing on diverse construction types and the hourly method of the annual energy calculations for continental and coastal climate areas in Croatia under the upcoming standards. Embodied carbon of diverse construction types was compared mutually, and required steps to meet the operational zero-emission standards were analyzed. Embodied energy of a 137.0 m^2 family house built out of reinforced concrete results in up to 67 tons of CO_2eq emissions, while wood in cross-laminated timber structures absorbs more carbon than emitted for all other materials and construction processes—23 tons of CO_2eq. Regarding operational energy and accompanying emissions, in order to cost-effectively meet future ZEB standards in Croatia and offset the remaining operational emissions, photovoltaic systems of up to 2.5 kWp are required in continental areas and 1.6 kWp in coastal regions.

Keywords: energy efficiency; embodied carbon; greenhouse gas emission; operational carbon; ZEB standard

1. Introduction

The building sector in the European Union (EU) consumes about 40% of total energy and, as such, has become a primary focus on climate policies and major economies, leading to a climate neutral Europe by 2050 [1,2]. The next step to carbon neutrality is zero-emission building (ZEB) standards which will come into force in the EU in 2028 for new buildings in public ownership and in 2030 for all new buildings [3]. Energy sources with low carbon emissions are mandatory for the current nearly zero-energy building (nZEB) standards as well as for the future ZEB standards [4]. In family buildings, such systems are electrically powered air-to-water heat pumps—one of the optimal solutions [5]. In heat pumps, electricity is used for the mechanical work of thermal energy transfer from, or to, the surrounding environment [6]. Heat pumps are used for heating, cooling, and domestic hot water (DHW) preparation.

Energy sources for electricity production include fossil fuels, nuclear energy, and renewable sources, mostly wind, hydro, and solar. Worldwide, the amount of fossil fuels in electricity production is steadily decreasing while being replaced by renewable sources. In Europe, electricity carbon intensity dropped from 641 g/kWh in 1991 to 207 g/kWh in 2023, with a downward trend expected to continue [7,8], whereas, in Croatia, electricity

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carbon intensity dropped from 302 g/kWh in 2000 to 174 g/kWh in 2024 [9]. Although fossil sources in electricity production are on the decline, they are still used during periods of high demand on the grid or when renewable sources are not available. Peak demands on the grid are still covered by the fossil-based power plants [10].

Current regulations regarding nZEB requirements vary greatly across the EU, from the strictest Danish regulations, which allow for 27 (kWh/(m^2 a)) of specific annual primary energy consumption in family houses, to the most lenient Romanian regulations, which allow for 158 (kWh/(m^2 a)) [11]. EU-wide, family houses are of very different levels of energy efficiency. Current regulations in Croatia are more demanding than EU benchmarks, with 45 kWh/(m^{2}a) for family houses in the continental parts of Croatia and 35 kWh/(m^2 a) for coastal areas [12]. For Croatia, the prescribed consumption of primary energy is among the lowest in the EU, meaning the energy efficiency of family houses is already at high levels.

Challenges in achieving the ZEB standards also lie in the availability of renewable energy, especially in the production of electricity. The EU countries with an unfavorable ratio of fossil fuels in their electricity mix face greater challenges in reducing annual operational energy emissions, such as Poland, with approximately 650 gCO_2eq/kWh. In the case of Croatia, hydropotential reduces electricity generation to below 200 gCO_2eq/kWh [13].

The potential for on-site electricity production and emission savings is much greater compared with electricity from the grid. Almost 500 gCO_2eq/kWh can be saved because fossil fuel power plants are still used for the residual demand of the load, which renewable sources cannot cover [14]. A series of goals are set for future buildings to achieve zero-emission standards. They will require high energy efficiency, use of 100% renewable energy, or production of energy on site. There is a disproportion in specific emissions of the electricity taken from the grid and potential savings in power plants when excess power is sent to the grid.

As stated in the EPBD 2024 recast, embodied carbon will be reported only informatively, while operational carbon will have to be zero (or almost zero) on the annual time frame [3]. If the forthcoming ZEB standards mandate that operational carbon is to be reduced to zero (or almost zero) annually, the only remaining emissions from buildings will be the ones related to embodied energy. Therefore, the main research questions of this study are what the amount of embodied carbon in various construction types is and what required steps are to nullify the operational carbon to meet the ZEB standards in family houses in Croatia.

Zero-emission buildings have existed as a concept for a few decades now, with different approaches in minimizing GHG emissions from buildings. At first, studies of the zero-emission concept concentrated only on the operational emissions, and then later, embodied emissions were also included. ZEB concepts that were able to offset embodied carbon proved to be difficult to achieve [15]. Previous research of specific embodied emissions in masonry construction resulted in 353 kgCO_2eq/m^2 and in 218 kgCO_2eq/m^2 in timber frame buildings in Ireland [16]. Different results were obtained in the UK—571 kgCO_2eq/m^2 in masonry structures and 385 kgCO_2eq/m^2 in off-site panelized timber frames; whole life carbon for multi-story buildings varied from 119 kgCO_2eq/m^2 for timber structures to 185 for reinforced structures [17,18]. The greatest emissions were exhibited in the analysis of residential masonry buildings in Hungary—ranging between 475 and 775 kgCO_2eq/m^2 [19].

Until the EPBD definition, previous ZEB definitions varied in the life cycle stages included in the calculation. The Norwegian net zero-emission building concept is proposed to offset both operational and embodied emissions by renewable energy generated on site. The idea of net zero-emission building is the "pay back" of the embodied energy emissions [20]. Electrical energy production on site is proven to be the key factor to

balancing out the annual emissions. Only the buildings with PV production manage to nullify the annual emissions [21]. The possibility of sending any excess power to the grid is essential in the decarbonization process [22]. Research that included PV modeling for a zero-emission neighborhood in Norway resulted in 850 kWp per 10.000 m^2 of building floor area to offset both operational and embodied emissions [23]. In similar research, a 2449 m^2 institute building in South Korea required 116 kWp of installed PV power, and 362 m^2 of PV panels were required for a 2405 m^2 office building in Italy [24,25].

2. Methodology

In the scope of Life Cycle Assessment (LCA) stages, all major steps resulting in major GHG emissions from a building are included in the calculation. The study evaluates the life cycle greenhouse gas emissions for two representative single-family houses—one located in a continental area and the other in a coastal area of Croatia—aiming to capture the impacts of the Product and Construction stage along with the Use stage n alignment with current European regulatory requirements (Table 1).

Table 1. Life Cycle Assessment stages included in the analysis (data adapted from EN 15978/CEN TC 350 [13]).

A	**Product and Construction Stage**		**Included**
A1	Raw material supply	Extraction, processing, and production of raw materials	Yes
A2	Transport	Transport to the manufacturing site	Yes
A3	Manufacturing	Manufacturing of construction materials and building elements	Yes
A4	Transport to the site	Transport to the construction site	Yes
A5	Construction/installation	Fuel and electricity use on the construction site	Yes
B	**Use Stage**		**Included**
B1	Use	Emissions during use (VOC, off-gassing of plastics. . .)	No
B2	Maintenance	Cleaning, servicing, and repainting	No
B3	Repair	Fixing damaged building components	No
B4	Replacement	Replacement of parts of a building whose lifespan is shorter than the lifespan of the building	Yes
B5	Refurbishment	Major renovation	Yes
B6	Operational energy use	Energy consumption for heating, DHW preparation, cooling, lighting, appliances, and ventilation	Yes
B7	Operational water use	Water supply, wastewater treatment, and associated emissions (can include DHW preparation instead of B6)	No
C	**End-of-Life Stage**		**Included**
C1	Deconstruction/demolition	Fuel and electricity use for machinery and equipment, dust, direct emissions	Yes
C2	Transport	Transport to treatment or disposal site	Yes
C3	Waste processing	Sorting, crushing, and preparation for further use	No
C4	Disposal	Landfilling, incineration, and decomposition due to improper disposal	No
D	**Benefits and Loads Beyond the System Boundary**		**Included**
D	Reuse, recovery, recycling potential	Credits/penalties for materials or energy recovered after end-of-life stages (material recycling, energy recovery, reuse potential)	No

The methodology includes the assessment of embodied and operational carbon, as shown in Figure 1. Different load-bearing structural solutions are analyzed to evaluate their influence on embodied emissions. Operational energy performance is calculated using an hourly time step and real electricity mix data, while photovoltaic production on site is considered to evaluate the building's potential to achieve zero-emission performance.

Calculation of embodied carbon is performed in Microsoft Office Excel (Version 2302). The code for calculation of operational energy is written in Visual Basic, Visual Studio (Version 17.13.5) programming language according to V. Soldo et al. [26].

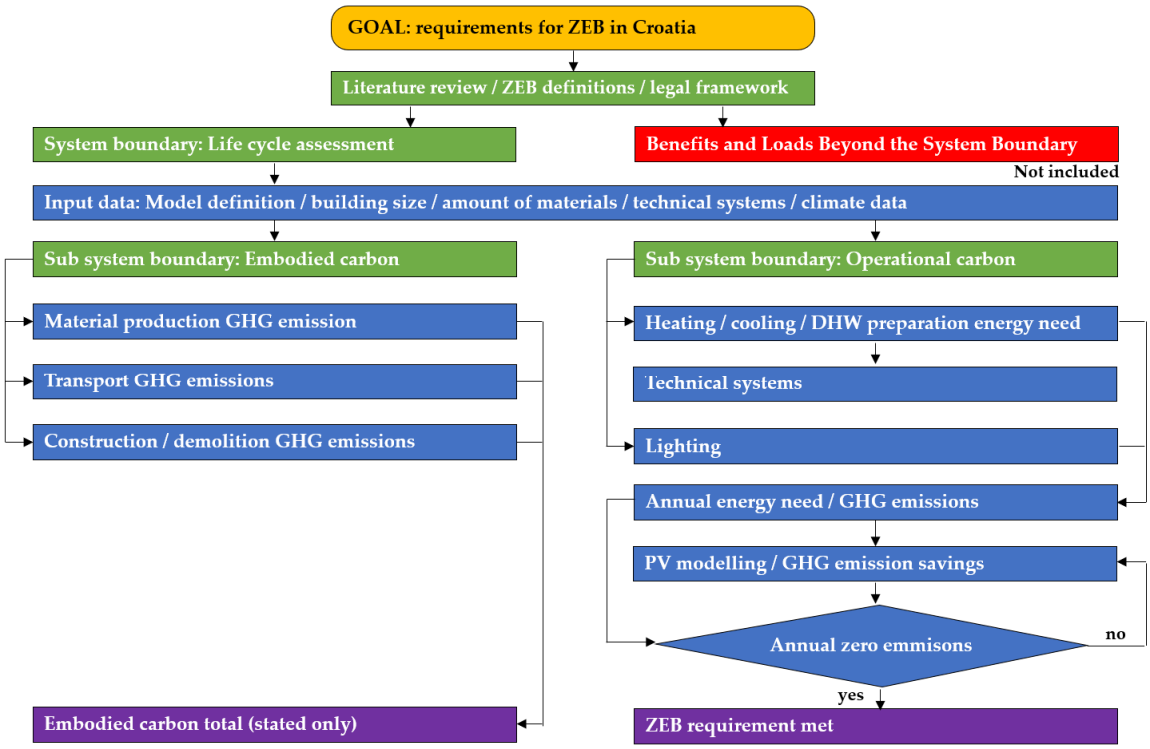


Figure 1. Determination of embodied and operational carbon.

2.1. Embodied Carbon

Embodied energy analysis was performed on a model of a 137.0 m^2 net area (182.4 m^2 gross area) single-family house, shown in Figure 2. Four major components of embodied energy were calculated in this analysis: built-in materials, refurbishment/renovation, material transport, and construction/deconstruction.



Figure 2. Case study: single-family house.

Embodied carbon is calculated according to following Equations (1)–(4).

$$E_{CO2eq,materials} = \sum_{i=1}^{n} m_{material,i} e_{material,i} \ (kgCO_2eq) \quad (1)$$

where E ($kgCO_2eq$) is the total GHG emissions, n (-) is the number of materials, m (kg) is the mass of the materials, and $e_{material}$ ($kgCO_2eq/kg$) is the specific material production CO_2eq emission. The same equation is used for the production emissions of built-in and reconstruction materials.

$$E_{CO2eq,transport} = \sum_{i=1}^{n} m_{material,i} d_{material,i} e_{transport} 10^{-6} \ (kgCO_2eq) \quad (2)$$

where d (km) is the material transport distance and $e_{transport}$ ($gCO_2eq/(t\ km)$) is the specific road transport emission of 57 $gCO_2eq/(t\ km)$. Distance includes both the delivery and the disposal distance of materials.

$$E_{CO2eq,(de)construction} = \sum_{i=1}^{n} m_{material,i} e_{(de)construction} 10^{-3} \ (kgCO_2eq) \quad (3)$$

where $e_{(de)construction}$ ($kgCO_2eq/ton$) is the specific construction and demolition emission.

Total embodied carbon is the sum of all the material production emissions, transport emissions, and construction and demolition emissions.

$$E_{CO2eq,total} = E_{CO2eq,materials} + E_{CO2eq,transport} + E_{CO2eq,(de)construction} \ (kgCO_2eq) \quad (4)$$

2.1.1. Built-In Materials (Stages A1, A2, A3)

Since embodied carbon primarily depends on the building material, six different types of load-bearing structures were evaluated: reinforced concrete, hollow clay block, porous clay block, aerated concrete block, wood-based sandwich panels, and cross-laminated timber. In the coastal areas of Croatia, masonry and reinforced concrete dominate because of traditional massive construction practices using stone due to availability of this material and its high thermal mass, which provided protection from the Mediterranean climate (high temperatures in summer and strong cold winds during winter). Massive materials also offered resistance to moisture and salt exposure, while timber was scarce and therefore used only when necessary. In contrast, inland regions have extensive forest resources, making timber locally available. From a traditional perspective, in rural regions wooden houses were also easier to heat up during winter, contributing to the widespread use of lightweight timber construction in traditional continental architecture, while masonry was more common for residences, high-rises, and public buildings. Nowadays, all types of construction equally coexist in continental Croatia. Consequently, all six types of construction are analyzed for continental areas, while only reinforced concrete and masonry structures are analyzed for coastal areas. Thermal properties of the envelope are designed according to the regulations for the continental and coastal parts of Croatia. The main difference is in the thickness of thermal insulation in the envelope or, in the case of porous clay block and aerated concrete, the thickness of the bearing wall. The number of other types of materials used in construction is the same for both houses in continental and coastal areas. Specific GHG emissions for material production are obtained from the Baubook Eco2Soft database, compliant with the environmental product declaration (EPD) standard EN 15804 (includes stages A1, A2, and A3) [27,28].

Timber constructions store carbon during a building's lifetime (50–100 years). Reuse of timber in various elements can prolong carbon storage for additional decades in forms of wood-based panels or construction materials again [29]. Despite the proven benefits, timber reuse and recycling are currently not used widely due to low demand for used

timber, lack of standards, and material damaged in deconstruction [30]. However, timber reuse is expected to increase in the following decades. The time frame observed in this analysis is 50 years, at which point, carbon should still be stored in the construction, as timber end-of-life emissions occur much later than the end of a building's life. Benefits and loads beyond the system boundary for construction materials are not accounted for.

2.1.2. Refurbishment/Renovation (Stages B4, B5)

The usual expected lifetime of a building is 50 years. Some of the building materials and elements are not that durable and must be replaced once or twice during the building's life cycle. Reconstruction during the usage phase of the building results in CO_2 emissions due to material production, the same as during the building phase. GHG emissions from the materials used in phases B4 and B5 also include stages A1, A2, and A3.

2.1.3. Material Transport (Stages A4, C2)

The total weight of materials used in building depends on the type of load-bearing construction. Materials of the greatest weight are used in reinforced concrete buildings, and materials of the least weight are used in light-frame or sandwich panels. Transport-related embodied carbon emissions include four stages of transport: bringing materials to the site for initial construction and later for reconstruction, transporting waste materials to the disposal site or recycling plant at the reconstruction phase, and at the end-of-life phase. Transport-related emissions depend on the type of transport, cargo weight, and distance. Use of locally produced materials is encouraged to reduce the distance of transport. Local transport distance can be considered within the same country or region, up to 300 km [27,31], or 100 km for delivery and 50–100 km for waste recycling or disposal [32]. In this case, transport distances were determined for all used materials and products for two reference cities—from the production site to the construction site in Zagreb and Split. Transport emissions vary by type of transport, with the greatest emissions per ton-km for road transport and the least for maritime transport. Local transport up to 100 km is done by trucks, and there is a difference in emissions for urban and long-haul transport. In urban traffic, emissions reach up to 307 $gCO_2eq/(t\ km)$ due to numerous stops at traffic lights and changes in speed, whereas long-haul transport is much more efficient, with approximately 57 $gCO_2eq/(t\ km)$ [33]. Material transport used in the building phase, reconstruction phase, and deconstruction phases are all accounted for in the transport emissions.

2.1.4. Construction/Deconstruction (Stages A5, C1)

Calculation of emissions related to construction and deconstruction is determined according to fuel and electricity use for machinery, direct process emissions, which include dust or Volatile Organic Compounds (VOC), and other considerations like time of the year, material recycling, etc. If detailed data are not available, estimates according to material amount and type are available—according to building floor area or according to the total mass of the material can be used. Construction-related emissions depend on the material being used for building; for concrete, it is approximately 9 $kgCO_2eq/m^3$ [34], which results in approximately 4.5 $kgCO_2eq$ per ton. For the deconstruction of concrete structures, estimates per gross floor area vary from 6.19 $kgCO_2eq/m^2$ to 17.7 $kgCO_2eq/m^2$ [35,36]. According to the mass of the materials in the deconstruction, the estimated range is between 4 and 10 $kgCO_2eq$ per ton [37]. In this analysis, an estimate according to the total mass of the materials was performed. A quantity of 5 $kgCO_2eq/ton$ was used for the calculation of construction and was the same for deconstruction emissions for all types of load-bearing construction. Emissions for construction and deconstruction are proportional to the weight of the built-in and reconstructed materials and vary greatly depending on the material of the construction.

2.2. Operational Carbon (Stage B6)

The goal of this work is to determine CO_2 emissions from electricity use in domestic households in continental and coastal areas of Croatia, as well as the needed energy production on site to achieve the zero-emission standards. Energy consumption in buildings varies throughout the day, just like photovoltaic electricity production. Also, electricity obtained from the grid is produced differently depending on the time of day. Therefore, a one-hour time step method was chosen for the calculation of energy consumption and energy production. Five primary aspects of operational energy were quantified: annual energy need, delivered energy, electricity mix, electricity production on site, and lighting.

2.2.1. Annual Energy Need

Analysis of operational carbon includes emissions from heating, domestic hot water (DHW) preparation, cooling, and lighting. Annual energy consumption for heating $Q_{H,nd}$ (kWh/a) and cooling $Q_{C,nd}$ (kWh/a) depend on the geometric and physical properties of the building (and ventilation system if applied, which is not the case in this research). The composition of the envelope determines the physical characteristics, which means that different types of load-bearing construction will result in different U (W/(m^2 K)) values of the envelope. Table 2 shows the physical characteristics and thickness of thermal insulation in the envelope for all analyzed cases. Annual energy need is calculated according to V. Soldo et al. [26], the hourly method using meteorological information for 8760 h in the year. One-hour time step meteorological data are available for Zagreb, which is a reference location for the continental climate area, and for Split, as a reference location for the coastal climate.

Table 2. Physical properties of the envelope, depending on the load-bearing construction, for the continental/coastal climate for the analyzed cases.

Building Element	Reinforced Concrete	Hollow Clay Block	Porous Clay Block	Aerated Concrete Block	Wood-Based Sandwich Panels	Cross-Laminated Timber
Wall insulation thickness (cm)	EPS 15/10 **	EPS 15/8 **	38 */30 *,**	38 */30 *,**	MW 16 + + EPS 10	EPS 15
U_{wall} (W/(m^2 K))	0.24/0.35 **	0.22/0.36 **	0.17/0.26 **	0.28/0.33	0.14	0.22
α_{wall} (-)	0.6	0.6	0.6	0.6	0.6	0.6
Floor insulation thickness (cm)	EPS 12/8 **	EPS 12/8 **	EPS 12/8 **	EPS 12/8 **	EPS 12	EPS 12
U_{floor} (W/(m^2 K))	0.29/0.41 **	0.29/0.41 **	0.29/0.41 **	0.29/0.41 **	0.29	0.29
Roof insulation thickness (cm)	MW 16 cm	MW 21 cm	MW 21 cm	MW 21 cm	MW 21 cm	MW 16 cm
U_{roof} (W/(m^2 K))	0.21	0.16	0.16	0.16	0.16	0.18
U_{door} (W/(m^2 K))	2.00	2.00	2.00	2.00	2.00	2.00
U_{blinds} (W/(m^2 K))	0.6	0.6	0.6	0.6	0.6	0.6
U_{window} (W/(m^2 K))	1.40	1.40	1.40	1.40	1.40	1.40
F_f (-)	0.7	0.7	0.7	0.7	0.7	0.7
$F_{C,C}$ (-)	0.3	0.3	0.3	0.3	0.3	0.3
$g_\perp$ (-)	0.6	0.6	0.6	0.6	0.6	0.6

* Thermal insulation of the wall is achieved by the thickness of load-bearing blocks. ** Slash-separated values refer to continental/coastal regions, while unified values apply equally to both cases.

2.2.2. Delivered Energy

The amount of energy delivered to DHW preparation and the heating and cooling systems depends on both the annual energy need and the type of system. The current obligatory energy standard in the EU is the nearly zero-energy building (nZEB), which is a standard commonly achieved by optimal envelope insulation and the use of renewable

energy sources, such as environmental heat used by heat pumps, biomass boilers, solar energy, etc. In this case, for both continental and coastal climates, an electrically powered air-to-water heat pump is used for heating, DHW preparation, and cooling, while energy production on site is achieved by photovoltaic panels. The time step used in the calculation of delivered energy is one hour according to EN 15316-4-2:2017 for heating and DHW preparation, CEN/TR 16798-14:2017 for cooling, and EN 15316-4-3:2017 for photovoltaic electricity production [38–40]. Table 3 shows properties of the heat pump required for the calculation of delivered energy and properties of photovoltaic panels required for the calculation of electricity production on site.

Table 3. Characteristics of technical systems for houses in the continental/coastal area.

Heating	**Value**
Heating capacity/output, A7/W50, ΦH (kW), according to Lončar et al. [41]	10/7 *
Balance temperature, Θ_b (°C)	−5
Floor heating, ηem (-)	0.9
Supply floor heating temperature, Θsup (°C)	40
Return floor heating temperature, Θret (°C)	30
DHW Preparation	
Hot water temperature, $\Theta_{w,del}$ (°C)	45
Storage tank capacity, $V_{st,w}$ (l)	300
Location of water storage tank	Inside
Cooling	
Chilled water 7/12 °C, refrigerant R410A, energy efficiency ratio, EER (-)	2.4
Single-zone system with continuous control, mean partial load factor, PLV_{av} (-)	1.37
Photovoltaic Panels	
Monocrystalline silicon, peak power coefficient, K_{pk} (-)	0.18
Moderately ventilated modules, installation-dependent efficiency factor, f_{perf} (-)	0.8
Reference solar irradiance, I_{ref} (-)	1
Overall efficiency, η_{PV} (-)	0.14
Panel orientation (azimuth angle), γ (°)	0 (S)
Panel tilt, β (°)	30

* Slash-separated values refer to continental/coastal regions, while unified values apply equally to both cases.

2.2.3. Electricity Mix

Energy sources for electricity production in the EU include fossil fuels, nuclear, and renewables (wind, solar, and hydro). Direct emissions in electricity production from nuclear and renewable sources are almost non-existent, while fossil sources result in up to 1.000 gCO_2eq/kWh.

The electricity mix varies throughout the day because it depends on the energy demand and available energy sources. Low energy demand can mostly be covered by renewables and nuclear power, but when demand peaks, compensation from fossil fuel power plants is required. Figure 3 shows average electricity production intensity in gCO_2eq/kWh by the hour in the day in Croatia for the year 2024, January 2024, June 2024, and 5 May 2024 (the day with the greatest variations in electricity production emissions).

Hourly information about real-time carbon intensity in electricity production for the year 2024 in Croatia is obtained from the Electricity Maps platform, which uses various sources. The source for the data used in this research is the European Network of Transmission System Operators for Electricity (ENTSO-E), which is an association of 39 transmission system operators (TSOs) from 35 European countries [42].

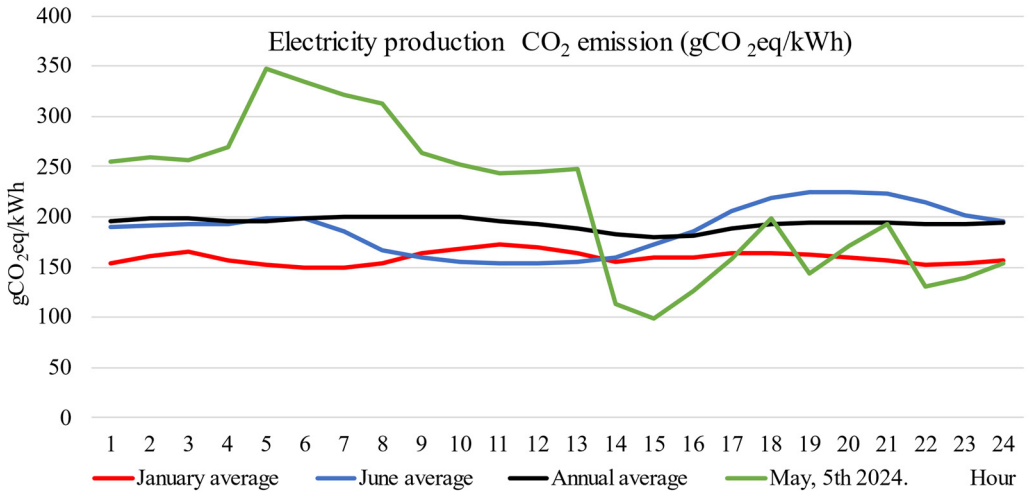


Figure 3. CO_2 emissions by the hour for electricity production in Croatia in 2024.

2.2.4. Electricity Production on Site

According to the EPBD 2024 recast, ZEBs will have to meet the standards of zero greenhouse gas emissions on site for building use, meaning only renewable sources of heating and cooling energy will be allowed. Regarding electricity, total annual primary energy use must originate from renewable sources, which can be ensured by purchasing renewable electricity from the grid or connecting to renewable energy communities. Production of electricity on site is recommended for use on site and for export to the grid, which increases available renewable supply and reduces CO_2 emissions.

In the ZEB variants in this research, PV panels are planned on site to determine the required amount of electricity produced and delivered to the grid to nullify the emissions from fossil fuel power plants annually. The model is designed to show how electricity from solar power plants is used in buildings if electricity is produced and how excess electricity is delivered to the grid when production surpasses the consumption. When demand for the building is greater than the production, residual demand is covered from the grid. Figure 4 shows the hourly distribution of electricity consumption and production for a day when excess energy is sent to the grid.

The CO_2 emissions from energy use for the cases, as shown in Figure 4, vary greatly. When power is used from the grid, greenhouse gas is emitted at the point of generation proportional to the current electricity mix. In Croatia, in 2024, average electricity generation was 194 gCO_2eq/kWh, while emissions varied from 48 gCO_2eq/kWh to 433 gCO_2eq/kWh depending on the grid load and availability of renewable sources. When energy production on the site is sufficient, there is no requirement for electricity use from the grid. That means each kWh used from a PV power plant results in no greenhouse gas emissions. In cases where excess electricity is sent to the grid, the potential for savings in CO_2 emissions is much greater.

The electricity mix for the EU in 2024 consisted of 48% renewables, 25% nuclear, 24% fossil fuels, and 3% other sources (oil, geothermal) [43]. Renewables and nuclear sources result in almost no emissions, while coal plants can emit more than 1.000 gCO_2eq per kWh, and highly efficient natural gas combined-cycle plants about 400 gCO_2eq per kWh [44]. In electricity production, energy sources are used in a certain order. Renewables produce electricity at low or no cost, so they are always used first. Nuclear power plants run at low fuel cost, but due to the design of the reactors, they are unable to increase or decrease output quickly. Fossil power plants have a higher fuel cost, and they are used lastly to cover residual or peak demand. When electricity is sent to the grid from on-site PV production plants, the amount of electricity from renewable sources in the grid increases

and the residual demand covered by fossil sources decreases. That means that every kWh of electricity sent to the grid will save the same amount of kWh of electricity from the fossil fuel power plants. According to the ENTSO-E hourly statistic for electricity carbon intensity in Croatia, in 2024, the average ratio of renewable electricity was 59%, with a 22% minimum and an 87% maximum, meaning that, at all times, fossil-based electricity was used from the grid in various amounts [44]. For Croatia, in 2024, only 3% of electricity was obtained from coal and 12% from gas combined-cycle plants with the carbon intensity of 530 gCO_2eq per kWh; the rest of the fossil emissions originated from imported electricity [42]. Considering that approximately 10% of typical electrical losses occur from PV modules to the appliances or the grid [45], 1 kWh of electricity produced and sent to the grid would increase the amount of available green electricity by 0.9 kWh and save 480 gCO_2eq emissions if the gas combined-cycle plant is displaced.

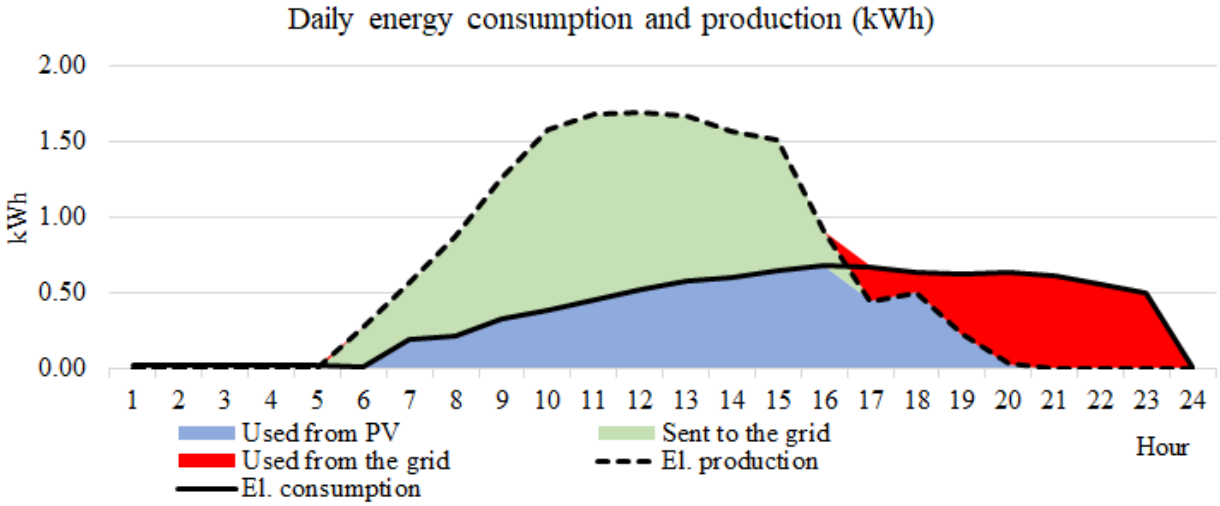


Figure 4. Hourly building energy consumption and photovoltaic production for a continental climate, 11 June.

2.2.5. Lighting

In residential buildings, lighting represents up to 10% of total energy consumption [46]. Such an amount is low compared with heating and cooling but cannot be ignored in greenhouse gas emissions analysis. Electricity consumption for lighting in Croatia is estimated to be 304 kWh/a for a household [47]. Since the time step for the analysis is one hour, it is important to consider when energy consumption and production occur during the day. For the analysis, it was estimated that lighting is used in the period between 7 a.m. and 11 p.m. and that lighting is used inversely proportional to solar irradiance—when solar irradiation in the exterior drops below 50 W/m^2 on a horizontal surface.

3. Results

3.1. Embodied Carbon

Embodied carbon emissions include the GHG emissions of built-in materials or materials used in reconstruction, transport-related emissions, and deconstruction at the end-of-life phase. Tables 4 and 5 show the mass of materials used in various types of construction in the construction and reconstruction phase for continental and coastal models. Construction- and reconstruction-related emissions are calculated from the bill of materials, as shown in Tables 6 and 7.

Table 4. Mass of built-in and reconstruction materials (kg) in a continental single-family house.

Load-Bearing Construction/ Material	Reinforced Concrete	Hollow Clay Block	Porous Clay Block	Aerated Concrete Block	Wood-Based Sandwich Panels	Cross-Laminated Timber	Transport Distance (km)
Reinforced concrete	286.480	103.850	95.870	80.333	44.173	44.173	21
Bitumen waterproofing	791	791	791	791	791	791	64
Hollow clay block	0	41.134	20.960	0	0	0	81
Roof tiles	3.593 (3.593)	3.593 (3.593)	3.593 (3.593)	3.593 (3.593)	3.593 (3.593)	3.593 (3.593)	60
Wooden door	364 (44)	364 (44)	364 (44)	364 (44)	364 (44)	364 (44)	130
Wooden elements	1.040 (210)	1.455 (210)	1.455 (210)	1.455 (210)	9.547 (210)	1.040 (210)	36
EPS	596 (399)	613 (399)	294	254	480 (266)	596 (399)	15
Cement screed	17.263	17.263	17.263	17.263	17.263	17.263	30
Gypsum board	1.822	2.944	2.944	2.944	7.864	1.822	60
Wall putty	0	0	0	3.280	0	0	30
Ceramics	662 (662)	662 (662)	662 (662)	662 (662)	662 (662)	662 (662)	200
Rain dam	22 (22)	22 (22)	22 (22)	22 (22)	22 (22)	22 (22)	147
Laminated wood	0	0	0	0	0	42.027	155
Metal construction	172	521	521	521	521	172	335
Mineral wool	501	632	632	632	1.847	501	60
OSB board	0	1.297	1.297	1.297	9.288	0	89
PE foil	51	51	51	51	90	51	21
PVC window	1.013 (1.013)	1.013 (1.013)	1.013 (1.013)	1.013 (1.013)	1.013 (1.013)	1.013 (1.013)	59
Parquet	1.611 (1.611)	1.611 (1.611)	1.611 (1.611)	1.611 (1.611)	1.611 (1.611)	1.611 (1.611)	25
Aerated concrete block	0	0	0	33.734	0	0	117
Extension plaster	16.244	14.447	24.024 (9.577)	9.577 (9.577)	0	0	19
Porous clay block	0	0	37.235	0	0	0	55
XPS	75	75	75	75	0	75	19
Finishing plaster	975 (975)	975 (975)	0	0	975 (975)	975 (975)	30
Gravel	20.376	22.704	22.704	22.704	23.868	23.868	19
Total (kg)	353.650 (8.529)	216.019 (8.529)	233.382 (7.155)	182.176 (16.732)	123.972 (8.396)	140.618 (8.529)	

Values in brackets represent reconstruction data.

Table 5. Mass of built-in and reconstruction materials (kg) in a coastal area single-family house.

Load-Bearing Construction /Material	Reinforced Concrete	Hollow Clay Block	Porous Clay Block	Aerated Concrete Block	Transport Distance (km)
Reinforced concrete	286.480	103.850	90.549	75.012	24
Bitumen waterproofing	791	791	791	791	461
Hollow clay block	0	41.134	20.960	0	487
Roof tiles	3.593 (3.593)	3.593 (3.593)	3.593 (3.593)	3.593 (3.593)	316
Wooden door	364 (44)	364 (44)	364 (44)	364 (44)	378
Wooden elements	1.040 (210)	1.455 (210)	1.455 (210)	1.455 (210)	26
EPS	391 (266)	355 (213)	182	234	20
Cement screed	17.263	17.263	17.263	17.263	12
Gypsum board	1.822	2.944	2.944	2.944	73
Wall putty	0	0	0	3.280	27

Table 5. *Cont.*

Load-Bearing Construction /Material	Reinforced Concrete	Hollow Clay Block	Porous Clay Block	Aerated Concrete Block	Transport Distance (km)
Ceramics	662 (662)	662 (662)	662 (662)	662 (662)	450
Rain dam	22 (22)	22 (22)	22 (22)	22 (22)	419
Laminated wood	0	0	0	0	360
Metal construction	172	521	521	521	215
Mineral wool	501	632	632	632	471
OSB board	0	1.297	1.297	1.297	490
PE foil	51	51	51	51	411
PVC window	1.013 (1.013)	1.013 (1.013)	1.013 (1.013)	1.013 (1.013)	450
Parquet	1.611 (1.611)	1.611 (1.611)	1.611 (1.611)	1.611 (1.611)	317
Aerated concrete block	0	0	0	29.513	347
Extension plaster	16.244	14.447	24.024 (9.577)	9.577 (9.577)	415
Porous clay block	0	0	29.396	0	235
XPS	75	75	75	75	403
Finishing plaster	975 (975)	975 (975)	0	0	420
Gravel	20.376	22.704	22.704	22.704	7
Total (kg)	353.445 (8.396)	215.761 (8.342)	220.110 (7.154)	172.615 (16.731)	

Values in brackets represent reconstruction data.

Table 6. Embodied carbon ($kgCO_2eq$) in a continental single-family house.

Load-Bearing Construction/ Material	Reinforced Concrete	Hollow Clay Block	Porous Clay Block	Aerated Concrete Block	Wood-Based Sandwich Panels	Cross-Laminated Timber	Specific Material Emissions ($kgCO_2eq/kg$)
Reinforced concrete	45.837	16.616	15.339	12.853	7.068	7.068	0.16
Bitumen waterproofing	340	340	340	340	340	340	0.43
Hollow clay block	0	7.404	3.773	0	0	0	0.18
Roof tiles	431 (431)	431 (431)	431 (431)	431 (431)	431 (431)	431 (431)	0.12
Wooden door	−364 (−44)	−364 (−44)	−364 (−44)	−364 (−44)	−364 (−44)	−364 (−44)	−1.00
Wooden elements	−1.040 (−210)	−1.455 (−210)	−1.455 (−210)	−1.455 (−210)	−9.547 (−210)	−1.040 (−210)	−1.00
EPS	2.485 (1.664)	2.556 (1.664)	1.226	1.059	2.002 (1.109)	2.485 (1.664)	4.17
Cement screed	2.072	2.072	2.072	2.072	2.072	2.072	0.12
Gypsum board	419	677	677	677	1.809	419	0.23
Wall putty	0	0	0	656	0	0	0.20
Ceramics	516 (516)	516 (516)	516 (516)	516 (516)	516 (516)	516 (516)	0.78
Rain dam	73 (73)	73 (73)	73 (73)	73 (73)	73 (73)	73 (73)	3.30
Laminated wood	0	0	0	0	0	−46.230	−1.10
Metal construction	205	620	620	620	620	205	1.19
Mineral wool	1.227	1.548	1.548	1.548	4.525	1.227	2.45
OSB board	0	−1.492	−1.492	−1.492	−10.681	0	−1.15
PE foil	168	168	168	168	297	168	3.30
PVC window	1.236 (1.236)	1.236 (1.236)	1.236 (1.236)	1.236 (1.236)	1.236 (1.236)	1.236 (1.236)	1.22
Parquet	548 (548)	548 (548)	548 (548)	548 (548)	548 (548)	548 (548)	0.34
Aerated concrete block	0	0	0	7.759	0	0	0.23
Extension plaster	2.599	2.312	3.844 (1.532)	1.532 (1.532)	0	0	0.16
Porous clay block	0	0	6.702	0	0	0	0.18
XPS	313	313	313	313	0	313	4.17
Finishing plaster	185 (185)	185 (185)	0	0	185 (185)	185 (185)	0.19
Gravel	204	227	227	227	239	239	0.01

Table 6. *Cont.*

Load-Bearing Construction/ Material	Reinforced Concrete	Hollow Clay Block	Porous Clay Block	Aerated Concrete Block	Wood-Based Sandwich Panels	Cross-Laminated Timber	Specific Material Emissions ($kgCO_2eq/kg$)
Materials total (kg)	57.454 (4.399)	34.532 (4.399)	36.343 (4.082)	29.318 (4.082)	1.367 (3.844)	−30.109 (4.399)	
Build phase	57.454	34.532	36.343	29.318	1.367	−30.109	
Reconstruction	4.399	4.399	4.082	4.082	3.844	4.399	
Transport	1.526	1.120	1.224	1.060	658	981	
(De)construction	3.622	2.245	2.405	1.989	1.324	1.491	
Total embodied	67.001	42.296	44.054	36.449	7.193	−23.238	
Specific embodied ($kgCO_2eq/m^2$)	489	309	322	266	53	−170	

Values in brackets represent reconstruction data.

Table 7. Embodied carbon ($kgCO_2eq$) in a coastal area single-family house.

Load-Bearing Construction/ Material	Reinforced Concrete	Hollow Clay Block	Porous Clay Block	Aerated Concrete Block	Specific Material Emissions ($kgCO_2eq/kg$)
Reinforced concrete	45.837	16.616	14.488	12.002	0.16
Bitumen waterproofing	340	340	340	340	0.43
Hollow clay block	0	7.404	3.773	0	0.18
Roof tiles	431 (431)	431 (431)	431 (431)	431 (431)	0.12
Wooden door	−364 (−44)	−364 (−44)	−364 (−44)	−364 (−44)	−1.00
Wooden elements	−1.040 (−210)	−1.455 (−210)	−1.455 (−210)	−1.455 (−210)	−1.00
EPS	1.630 (1.109)	1.480 (888)	759	976	4.17
Cement screed	2.072	2.072	2.072	2.072	0.12
Gypsum board	419	677	677	677	0.23
Wall putty	0	0	0	656	0.20
Ceramics	516 (516)	516 (516)	516 (516)	516 (516)	0.78
Rain dam	73 (73)	73 (73)	73 (73)	73 (73)	3.30
Laminated wood	0	0	0	0	−1.10
Metal construction	205	620	620	620	1.19
Mineral wool	1.227	1.548	1.548	1.548	2.45
OSB board	0	−1.492	−1.492	−1.492	−1.15
PE foil	168	168	168	168	3.30
PVC window	1.236 (1.236)	1.236 (1.236)	1.236 (1.236)	1.236 (1.236)	1.22
Parquet	548 (548)	548 (548)	548 (548)	548 (548)	0.34
Aerated concrete block	0	0	0	6.788	0.23
Extension plaster	2.599	2.312	3.844 (1.532)	1.532 (1.532)	0.16
Porous clay block	0	0	5.291	0	0.18
XPS	313	313	313	313	4.17
Finishing plaster	185 (185)	185 (185)	0	0	0.19
Gravel	204	227	227	227	0.01
Materials total (kg)	56.599 (3.844)	33.456 (3.623)	33.613 (4.082)	27.412 (4.082)	
Build phase	56.599	33.456	33.613	27.412	
Reconstruction	3.844	3.623	4.082	4.082	
Transport	2.210	2.715	2.973	2.088	
(De)construction	3.618	2.241	2.273	1.893	
Total embodied	66.272	42.035	42.941	35.476	
Specific embodied ($kgCO_2eq/m^2$)	484	307	313	259	

Values in brackets represent reconstruction data.

Tables 6 and 7 show total embodied carbon for various types of load-bearing construction in continental and coastal regions.

3.2. Operational Carbon

The annual energy needs of the building for heating, DHW preparation, cooling, and lighting is shown in Table 8 for the continental climate zone. Because of highly efficient heat pumps, the energy delivered to the technical systems is several times smaller than the need. Energy consumption, in combination with energy production, is shown in the second part of the table.

Table 8. Annual energy and GHG emissions balance for a continental single-family house.

Load-Bearing Construction	Reinforced Concrete	Hollow Clay Block	Porous Clay Block	Aerated Concrete Block	Wood-Based Sandwich Panels	Cross-Laminated Timber
$Q_{H,nd}$ (kWh/a)	8.340	7.449	6.672	7.800	6.312	7.366
$Q_{W,nd}$ (kWh/a)	1.713	1.713	1.713	1.713	1.713	1.713
$Q_{C,nd}$ (kWh/a)	3.051	3.468	3.554	3.780	3.924	3.852
$Q''_{H,nd}$ (kWh/(m^2 a))	60.88	54.37	48.70	56.94	46.07	53.76
$Q''_{C,nd}$ (kWh/(m^2 a))	12.50	12.50	12.50	12.50	12.50	12.50
$E_{del,H}$ (kWh/a)	3.168	2.980	2.579	3.158	2.572	3.026
$E_{del,W}$ (kWh/a)	724	734	724	738	733	739
$E_{del,C}$ (kWh/a)	998	1.153	1.177	1.230	1.274	1.268
$E_{del,light}$ (kWh/a)	304	304	304	304	304	304
$E_{del,total}$ (kWh/a)	5.195	5.172	4.784	5.430	4.883	5.337
$A_{FN,ef}$ (m_2)	13.7	13.8	12.9	14.4	13.3	14.3
P_{PV} (kWp)	2.5	2.5	2.3	2.6	2.4	2.6
$E_{el,PV}$ (kWh/a)	2.893	2.912	2.734	3.058	2.808	3.025
$E_{el,PV}/E_{del}$ (%)	56%	56%	57%	56%	58%	57%
$E_{el,PV,used}$ (kWh/a)	1.308	1.363	1.330	1.432	1.395	1.446
$E_{el,PV,exp}$ (kWh/a)	1.585	1.549	1.404	1.627	1.413	1.579
$E_{el,grid\ use}$ (kWh/a)	3.887	3.809	3.454	3.998	3.488	3.891
PV GHG savings = GHG grid use ($kgCO_2eq/a$)	761	744	674	781	678	758

Figure 5 shows annual electricity consumption and production (kWh/a) for the continental family houses, and Figure 6, shows comparison of embodied and operational life cycle GHG emissions ($kgCO_2eq$).

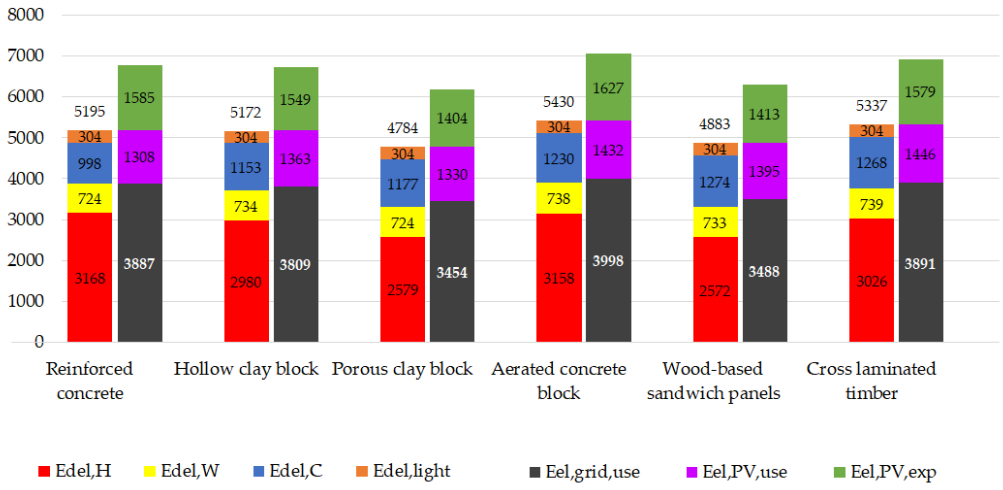


Figure 5. Annual electricity consumption/production (kWh/a) for a continental single-family house.

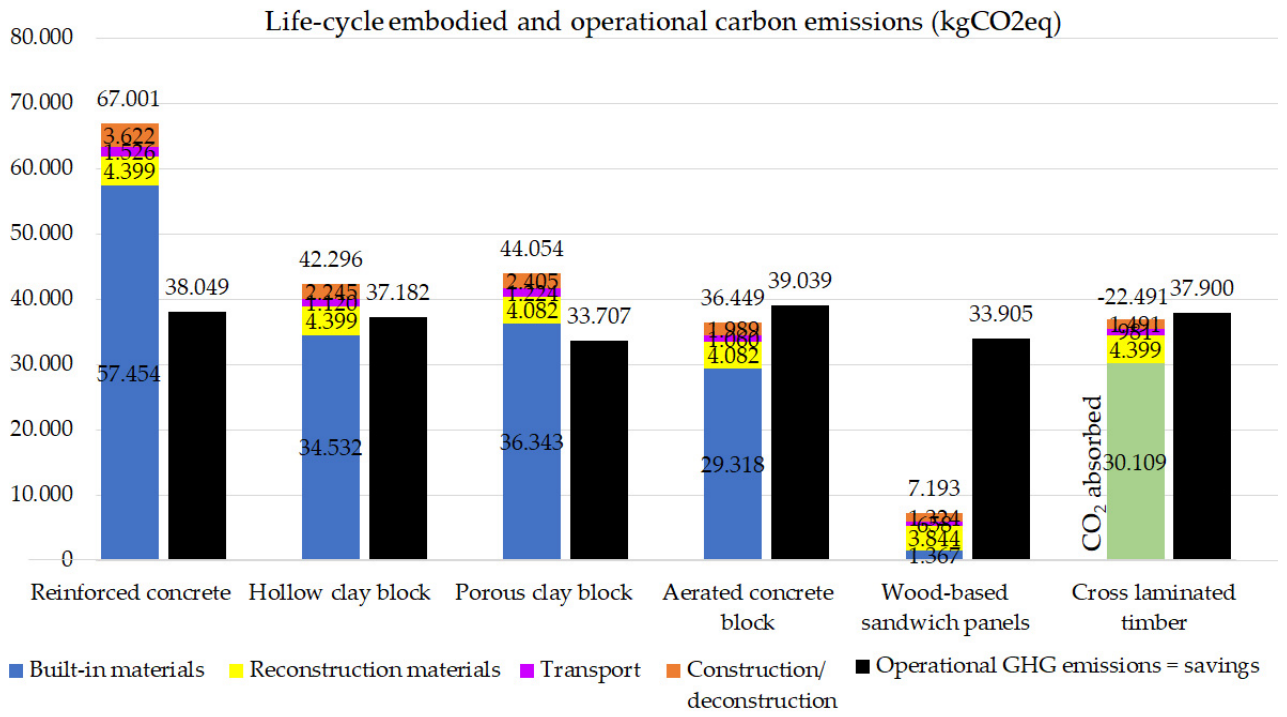


Figure 6. Comparison of lifetime embodied and operational life cycle GHG emissions (kgCO_2eq) for a continental single-family house.

The annual energy need is shown in Table 9 for the coastal climate zone. Figure 7 shows annual electricity consumption and production (kWh/a) for the continental family houses, while Figure 8 shows comparison of embodied and operational life cycle GHG emissions (kg CO_2eq).

Table 9. Annual energy and GHG emissions balance for a coastal area single-family house.

Load-Bearing Construction	Reinforced Concrete	Hollow Clay Block	Porous Clay Block	Aerated Concrete Block
$Q_{H,nd}$ (kWh/a)	4.108	3.875	3.150	3.526
$Q_{W,nd}$ (kWh/a)	1.713	1.713	1.713	1.713
$Q_{C,nd}$ (kWh/a)	4.719	4.960	4.913	5.038
$Q''_{H,nd}$ (kWh/(m^2 a))	29.99	28.28	22.99	25.74
$Q''_{C,nd}$ (kWh/(m^2 a))	34.44	36.20	35.86	36.77
$E_{del,H}$ (kWh/a)	1.037	1.008	784	923
$E_{del,W}$ (kWh/a)	626	630	626	629
$E_{del,C}$ (kWh/a)	1.515	1.599	1.589	1.626
$E_{del,light}$ (kWh/a)	304	304	304	304
$E_{del,total}$ (kWh/a)	3.483	3.541	3.304	3.482
$A_{FN,ef}$ (m_2)	9.1	9.3	8.7	9.1
P_{PV} (kWp)	1.6	1.7	1.6	1.6
$E_{el,PV}$ (kWh/a)	2.244	2.270	2.143	2.241
$E_{el,PV}/E_{del}$ (%)	64%	64%	65%	64%
$E_{el,PV,used}$ (kWh/a)	1.368	1.381	1.332	1.374
$E_{el,PV,exp}$ (kWh/a)	876	890	811	867
$E_{el,grid\ use}$ (kWh/a)	2.115	2.160	1.972	2.108
PV GHG savings = GHG grid use (kgCO_2eq/a)	420	427	389	416

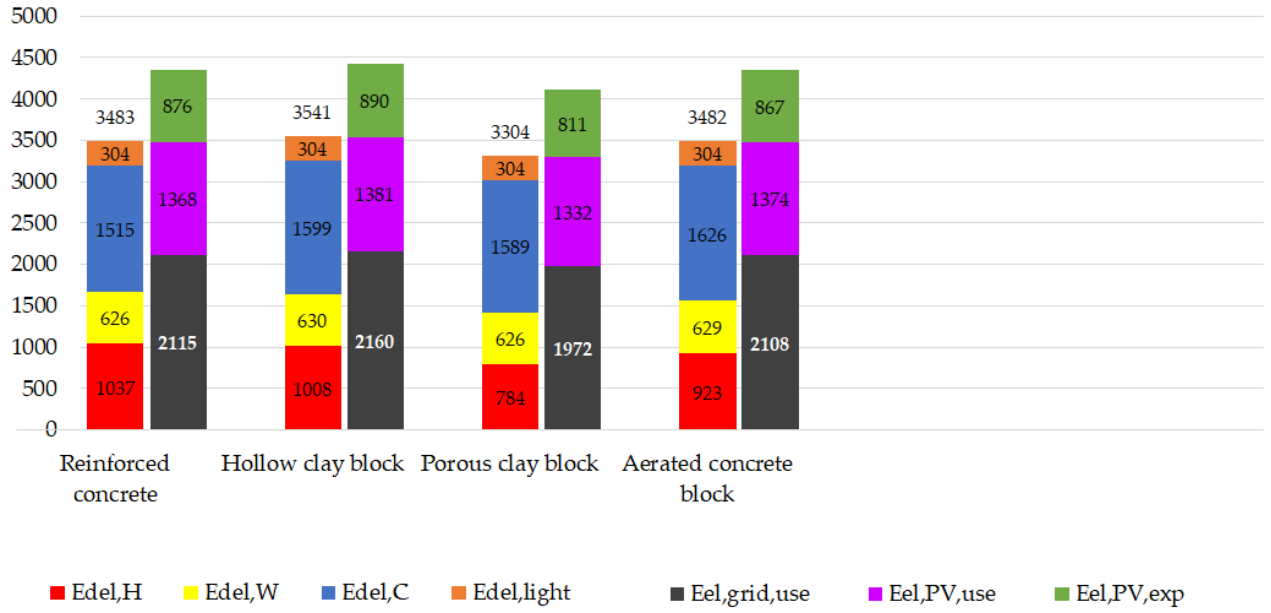


Figure 7. Annual electricity consumption/production (kWh/a) for a coastal area single-family house.

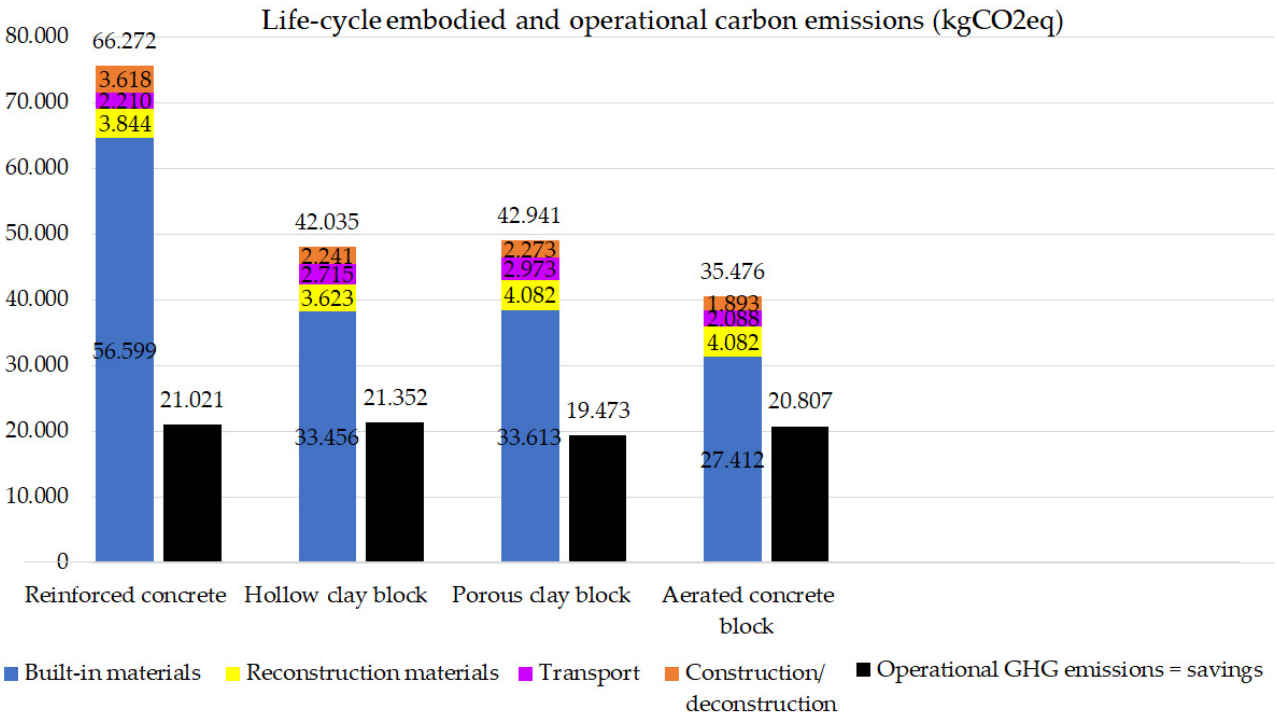


Figure 8. Comparison of lifetime embodied and operational life cycle GHG emissions ($kgCO_2eq$) for a coastal area single-family house.

4. Discussion

4.1. Embodied Carbon

GHG emissions from material production represent the greatest share of embodied carbon. Table 8 shows the four main components of embodied energy emissions: built-in materials, refurbishment, transport, and construction/deconstruction activities.

It can be observed that built-in materials make up most of the total embodied emissions. The mass of the built-in materials can be seen in Table 4. Due to their notable contribution to the total material mass, load-bearing structures have a major influence on embodied emissions. Reinforced concrete structures are responsible for the greatest

specific emissions of 484–489 $kgCO_2eq/m^2$ for houses both in continental and coastal areas of Croatia, primarily due to cement production emissions. Masonry houses follow with similar results, which are approximately 307–309 $kgCO_2eq/m^2$ for hollow clay blocks, 313–322 $kgCO_2eq/m^2$ for porous clay blocks, and 259–266 $kgCO_2eq/m^2$ for aerated concrete blocks. The lowest share of embodied carbon is in the massive timber walls and slabs, which have large amount of timber beams and OSB boards; wood-based sandwich panels account for only 53 $kgCO_2eq/m^2$, while cross-laminated timber (CLT) results in 170 $kgCO_2eq/m^2$ absorbed due to carbon sequestration in biomass. The results considering concrete and masonry constructions are in line with previous research [16–18], while timber constructions show much lesser values compared with others [16]. Such a difference is due to the assumption that at the building's end-of-life phase, timber will not be burned or landfilled but reused and recycled. That way, carbon will be stored for another 30–50 years. Table 6 shows material production-related GHG emissions. Figures 6 and 8 confirm that built-in carbon represents the dominant share of embodied emissions across all types of construction, while other stages of embodied emissions, including construction-related emissions, retrofit, transportation, and end-of-life phases, contribute in a comparatively minor way.

4.2. Operational Carbon

As noted in the introduction, Croatian nZEB requirements are among the strictest in the EU. Annual delivered energy and electricity production requirements, as shown in Table 9, confirm that delivered electricity consumption results in comparatively low greenhouse gas impacts. Due to the efficient building envelope and highly efficient heat pumps, the delivered energy for heating, cooling, and DHW is considerably lower than the building's energy demand. For continental cases, annual specific heating energy consumption ranges from 54 to 61 $kWh/(m^2\ a)$, and for coastal cases, 23 to 30 $kWh/(m^2\ a)$, depending on the type of construction. Such consumption for heating is optimal and represents energy performance class B–C for continental cases and classes A–B for coastal cases. Despite Croatia's relatively low grid carbon intensity (<200 gCO_2eq/kWh), electricity consumption still contributes to operational emissions. Therefore, photovoltaic systems are introduced to offset emissions by reducing electricity drawn from fossil-based generation. The findings confirm that photovoltaic production is shown to provide disproportionate emission savings. Approximately 56% of the total energy needs of the building must be produced by a photovoltaic (PV) power plant on site to nullify the operational emissions in continental regions of Croatia and approximately 64% in coastal areas. To reach the zero-emission status for a 137.0 m^2 family house, the required PV installed power is, on average, 2.5 kWp for continental family houses with a PV yield of 1.176 kWh/kWp. In coastal areas, the average PV installed power is 1.6 kWp with a PV yield of 1.364 kWh/kWp. Compared with previous research, a smaller PV power plant can suffice due to lower electricity carbon intensity in Croatia than in analyzed countries (Korea and Italy) as well as different building use [24,25]. The PV power plant modeled for the case in Norway is relatively larger because it must also offset embodied carbon emissions [23].

5. Conclusions

This research demonstrates that both embodied and operational carbon must be addressed when designing new zero-emission homes. Built-in materials—particularly the structural systems—have the highest share of embodied emissions, with reinforced concrete showing the worst performance on account of intense emissions in cement production. On the contrary, cross-laminated timber constructions are the most environmentally friendly in terms of GHG emissions. Wooden elements have a negative emission because more CO_2

is absorbed in the structure of the wood than is released for its production (stages A1, A2, and A3). For a massive cross-laminated timber structure, the amount of absorbed carbon is three times greater than the emissions for all other built-in materials.

The high energy efficiency of new buildings, low carbon intensity of electricity, and the use of fossil fuel power plants in electricity production create favorable conditions for the ZEB standards in Croatia. Operational emissions in Croatia are already comparatively low due to the favorable electricity mix and high energy efficiency standards for new buildings. In the ZEB model proposed in this paper, the results confirm that electricity production planned on site for use in the building is sufficient to offset residual emissions and enable annual zero-emission operation in both continental and coastal climates, showing the optimal level of energy efficiency of the analyzed family houses.

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Abbreviations

The following abbreviations are used in this manuscript:

EPS	Expanded polystyrene (thermal insulation)
MW	Mineral wool (thermal insulation)
XPS	Extruded polystyrene (insulation)
nZEB	Nearly zero-energy building
ZEB	Zero-emission building
$A_{PV,ef}$ (m^2)	Effective photovoltaic module area
$E_{del,C}$ (kWh/a)	Delivered energy for space cooling
$E_{del,H}$ (kWh/a)	Delivered energy for space heating
$E_{del,light}$ (kWh/a)	Delivered energy for lighting
$E_{del,total}$ (kWh/a)	Total delivered energy
$E_{del,W}$ (kWh/a)	Delivered energy for domestic hot water
$E_{el,grid\ use}$ (kWh/a)	Electricity imported from the grid
$E_{el,PV}$ (kWh/a)	Electricity generated by PV system
$E_{el,PV,exp}$ (kWh/a)	PV electricity exported to grid
$E_{el,PV,used}$ (kWh/a)	On-site used PV electricity
P_{PV} (kWp)	PV installed power
GHG emissions ($kgCO_2eq/a$)	Operational greenhouse gas emissions
PV GHG savings ($kgCO_2eq/a$)	Avoided GHG from PV replacing grid electricity
$Q''_{C,nd}$ (kWh/(m^2 a))	Net specific space cooling demand (per floor area)
$Q''_{H,nd}$ (kWh/(m^2 a))	Net specific space heating demand (per floor area)
$Q_{C,nd}$ (kWh/a)	Net space cooling demand
$Q_{H,nd}$ (kWh/a)	Net space heating demand
$Q_{W,nd}$ (kWh/a)	Net domestic hot water demand

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