POLİTEKNİK DERGİSİ

JOURNAL of POLYTECHNIC

ISSN: 1302-0900 (PRINT), ISSN: 2147-9429 (ONLINE)

URL: http://dergipark.org.tr/politeknik

Analysis of the embodied and operational energy of wood-based prefabricated panels produced with different design concepts according to vernacular Baghdadi wall

Farklı tasarım konseptleri ile üretilen ahşap esaslı prefabrike panellerin yerel Bağdadi duvara göre gömülü ve operasyonel enerji analizi

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To cite to this article: Akkan Çavdar A. & Vural N., "Analysis of the embodied and operational energy of wood-based prefabricated panels produced with different design concepts according to vernacular Baghdadi wall", ***Journal of Polytechnic***, 27(4): 1491-1503, (2024).

Bu makaleye şu şekilde atıfta bulunabilirsiniz: Akkan Çavdar A. ve Vural N., "Analysis of the embodied and operational energy of wood-based prefabricated panels produced with different design concepts according to vernacular Baghdadi wall", ***Politeknik Dergisi***, 27(4): 1491-1503, (2024).

Erişim linki (To link to this article): http://dergipark.org.tr/politeknik/archive

DOI: 10.2339/politeknik.1239942

Analysis of the Embodied And Operational Energy of Wood-Based Prefabricated Panels Produced with Different Design Concepts According to Vernacular Baghdadi Wall

Highlights

- *A comparison of the carbon emissions of prefabricated facade panels with different concept*
- *Identifying the prefabricated facade panel design concept that is the most environmentally friendly to be favored over the traditional Baghdadi wall*
- *Obtaining the proportion of operational and embodied energy-based carbon emissions in total carbon emissions*

Graphical Abstract

In this study, the operational and embodied energy-based carbon created by prefabricated facade panels with various design concepts was calculated numerically.

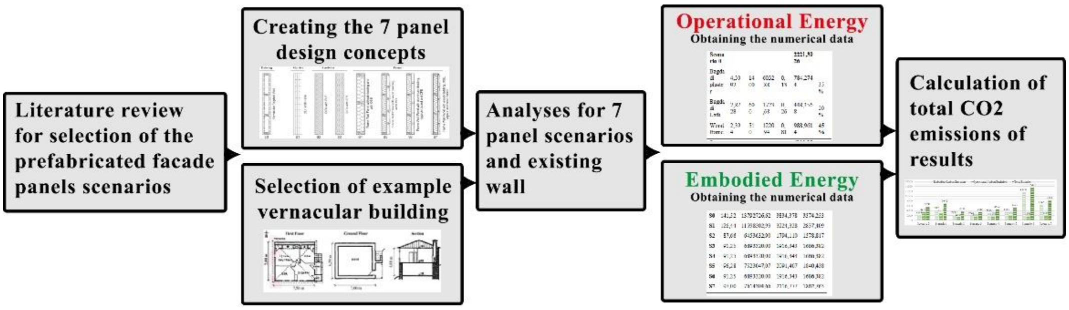

Figure. Workflow of the study

Aim

The main aim of the study is to obtain the operational and embodied carbon produced by wood prefabricated facade panels and compare them in terms of energy efficiency.

Design & Methodology

Numerical calculations were made with the data obtained from TS 825 and ICE sources.

Originality

There is no review in the literature in terms of sustainability or energy efficiency for wood-based prefabricated facade panels discussed in this study. The study will guide the designers in choosing the panel concept.

Findings

It is seen that the frame panel—which comprises metal elements—has the greatest embodied carbon emission at 87%. The CLT was the least energy-efficient scenario with 15.9%, and the sandwich panel with PUR was the most energy-efficient scenario with 53.21%.

Conclusion

The most energy-efficient wood prefabricated facade panel was the sandwich. In general, it is concluded that embodied carbon is more effective than operational carbon.

Declaration of Ethical Standards

The author(s) of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

Analysis of the Embodied and Operational Energy of Wood-Based Prefabricated Panels Produced with Different Design Concepts According to Vernacular

Research Article

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(Received : 20.01.2023 ; Accepted : 16.06.2023 ; Early View : 03.09.2023)

ABSTRACT

Prefabricated facade panels are building components that evolve with technology and offer a wide range of material possibilities. These panels can be constructed using wood, metal, concrete, or terracotta-based materials and are designed based on three concepts: massive, sandwich, and frame. In recent years, as sustainable design takes the spotlight, it is crucial to consider not only energy consumption and carbon emissions from heating and cooling but also the carbon emissions associated with the materials used in construction. This study aims to analyze prefabricated facade panels with wooden structures in terms of operational and embodied energy, providing guidance to designers in selecting suitable concepts. Calculations were conducted on a selected sample building. Compared to the traditional Baghdadi wall, the sandwich panel scenario with PUR insulation material resulted in energy savings of 53.21 percent. The massive CLT panel, which lacks insulation material or cladding, showed the lowest energy gain at 15.91 percent. Considering the overall emissions in the analysis, it has been determined that embodied carbon emissions have a greater impact than operational carbon emissions. Therefore, it is essential to emphasize the significant role of material selection for prefabricated facade panels in reducing carbon emissions.

Keywords: Prefabricated facade panels, Baghdadi wall, operational energy, embodied energy, carbon emission.

Farklı Tasarım Konseptleri ile Üretilen Ahşap Esaslı Prefabrike Panellerin Yerel Bağdadi Duvara Göre Gömülü Ve Operasyonel Enerji Analizi

ÖZ

Prefabrike cephe panelleri teknoloji ile gelişen ve malzeme olanakları ile çeşitlenen yapı elemanlarıdır. Ahşap, metal, beton veya pişmiş toprak esaslı taşıyıcı malzemelerden üretilebilen bu panellerin üç tasarım konsepti bulunmaktadır: masif, sandviç ve çerçeve. Sürdürülebilir tasarımın ön planda olduğu son yıllarda ısıtma ve soğutma kaynaklı enerji tüketimi ve karbon emisyonlarının yanı sıra binalarda kullanılan malzemelerin ürettiği karbon emisyonları da önemli rol oynamaktadır. Bu çalışma, ahşap taşıyıcıya sahip masif, sandviç ve çerçeve prefabrike cephe panellerinin operasyonel ve gömülü enerji açısından incelenmesini ve karşılaştırılmasını amaçlamaktadır. Bu kapsamda seçilen örnek yerel bina üzerinden hesaplamalar yapılmıştır. Binanın sahip olduğu Bağdadi duvar ile karşılaştırıldığında, PUR yalıtım malzemesine sahip sandviç panel senaryosu %53.21 oranında enerji tasarrufu sağlamıştır. En az enerji kazancı ise %15.91 oran ile herhangi bir yalıtım ve kaplama içermeyen masif CLT panelde görülmüştür. Yapılan analizde toplam emisyon miktarları dikkate alındığında, gömülü karbon emisyonunun operasyonel karbon emisyonundan daha etkili olduğu tespit edilmiştir. Bu doğrultuda prefabrike cephe panellerinde yer alacak malzeme seçiminin önemi dikkat çekmektedir.

Anahtar Kelimeler: Prefabrike cephe panelleri, Bağdadi duvar, operasyonel enerji, gömülü enerji, karbon emisyon.

1. INTRODUCTION

The building sector has the greatest potential to reduce greenhouse gas emissions, according to Kolodiy & Capeluto [1]. Therefore, buildings need to become efficient energy providers as well as consumers. The housing industry in Turkey is also the sector with the highest energy consumption after the transportation sector. For this reason, the design of systems that concern the building's energy performance in a house is important. Turkey is among the countries that work on energy conservation. In 2008, with the "By-Law on Energy Performance of Buildings", the principles for the effective and efficient use of energy resources were regulated and the existing "TS 825 Standard of Thermal Insulation Requirements for Buildings" was renewed, and the attention was drawn to energy conservation [2]. Contrary to studies on systems that will affect building energy use in Turkey, there is no regulation regarding material-based greenhouse gas emissions and building embodied energy use. The building energy performance evaluation for the Energy Performance Certificate is

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given only within the scope of operational energy use and carbon emissions produced because of this use [3].

The Energy sector is the sector causing the biggest greenhouse gas emissions in Turkey. While Turkey's total carbon emission value was 219.7 CO2 in 1990, this value reached 523.9 CO2 in 2020. 83% of this value covers the energy sector, including the construction and industrial processes, and product use sectors [4]. Different sectors should be encouraged to use renewable energy to reduce greenhouse gas emission values. Especially in Turkey, which is a repository in sunlight, buildings can produce energy using sunlight, and greenhouse gas emissions can be reduced [5]. In addition to the energy sources used in the buildings; the type of the building and the materials used in its construction have an important role in terms of the energy consumption of the building. Energy savings can be achieved with appropriate building materials [6]. Demirsoy & Sozen [7] emphasized that Energy Identity Certificate applications should be carried out effectively in order to increase energy efficiency in buildings. In this direction, they indicated that renewable energy sources should be encouraged, tax reductions should be provided, and projects should be carried out with the public.

In terms of building energy use, the periods during the life cycle of the building are important. Building Life Cycle Assessment (LCA), which was created in this direction, includes the product, construction, use, end of life, and beyond the system boundary stages [8]. There are sustainability parameters that affect these stages throughout the building life cycle. These parameters can be specified as water consumption impact, energy impact, well-being impact and materials impact [9]. When the cost of a building in use and maintenance stages are added up, the life cycle cost is considered worth the result because of the savings compared to the initial cost. Therefore, an architect needs to plan energy use in the design approach [10]. The overall energy consumption of a building is not only dependent on factors during use; It also depends on the design of the structure, the materials used, the method of construction and how its life cycle is managed. Accordingly, it is important to use advanced construction methods instead of traditional construction methods to design a structure with high energy performance. One of the solutions is also that was shown the tendency to prefabricated construction systems. Prefabricated manufacturing improves the construction process and delivers a high-quality end product [11].

Recently, the focus has been on the energy use of building materials (embodied energy) as well as operational energy expenditures to ensure energy efficiency. It is seen that there is an increase in temperature with global warming and the use of embodied energy is included in energy policies due to climate change [12]. Building designs can be realized by developing various parametric analysis tools that optimize both operational and embodied energy expenditures. This method allows different solutions to be compared, and convenient solutions can be selected [13]. Iddon et al. [14] estimated the embodied and operational carbon ratios that a detached house produces simultaneously over its 60-year life using a Building Information Model (BIM) tool they developed. As a result, 20-26% of the 60-year total carbon emissions are the cause of embodied, while 74-80% of them are caused by operational carbon emissions. It has been seen with other studies examined that; material changes in the building envelope to reduce excess operational carbon often increase embodied carbon. Accordingly, it is necessary to evaluate both operational and embodied carbon simultaneously, and transport, waste, and construction energy parameters can be included for a more advanced calculation. Yang & Li [15] calculated the embodied environmental impact of various balcony design concepts and employed the concept of life cycle assessment to quantitatively quantify the balcony's carbon emissions.

Hammond and Jones aimed to create an inventory for the embodied energy and carbon emission values of materials in the project (Inventory of Carbon & Energy, ICE) [16] that they started in 2005 and supported by the University of Bath. They obtained the best average coefficients by combining the data collected from secondary sources such as scientific articles, LCA research, books, etc. In this study, which includes more than 1700 sources, the materials are divided into 34 main groups. In another study, thinks that the amount of embodied energy will cause more serious environmental effects than operational energy use, the amount of carbon produced, and the energy consumed by parking garages with different construction systems and different materials (pre-cast concrete, post-tensioned concrete, cellular steel, and mass timber) calculated and compared with the numerical data in the ICE database [34]. Massive wood was seen as advantageous when it comes to embodied carbon and energy performance. In addition, it has been emphasized that details such as milling and manufacturing of structural wood greatly affect the environmental impact of the material [17]. Rodrigues et al., after obtaining electricity, water, and fuel parameters at the construction site for the Life Cycle Analysis (LCA) of an industrial building, conducted an embodied carbon and energy analysis for building materials with data from the ICE database [18]. In another study, examining the material selection of the exterior wall systems of five selected hotel buildings in Istanbul, the U values of the walls were calculated. Then, the annual heating energy and the resulting CO2 amount caused, and embodied carbon dioxide amounts were calculated. In the study, the sustainability of the exterior walls was desired to be examined comprehensively [19]. Studies show that embodied carbon has been included in comparisons, with operational energy and operational carbon, in recent years.

It is possible to offer different solutions as a façade system for existing and to be strengthened buildings to reduce the use of embodied energy. It is known that innovative materials, recycled, bio-based materials can be preferred in facade construction, as well as natural, carbon-storing, conventional, and industrialized materials such as wood can reduce environmental impacts [20]. Zang et al. [21] emphasize that the structures must be built with appropriate forms that respond to the local climate and meet the criterion for comfort. Prefabricated facade panels, which are prefabricated products, are components that can help reduce operational energy use. Thanks to the construction-insulation materials and appropriate material thicknesses they contain, they provide indoor comfort conditions. In addition, it is very important to calculate the amount of embodied energy of the panels for sustainability [22].

The literature research shows that analyses are generally made on different construction systems and structure component materials for operational and embodied carbon from buildings. In this direction, researches on facade systems are very few. There is no review for prefabricated facade panels produced with prefabrication, which provides a particularly fast construction. Wood material, which is seen as a sustainable material, is preferred as a suggested building material for building embodied carbon calculation.

Within the scope of the study, it is aimed to examine and compare the scenarios of prefabricated facade panels with wooden structure systems consisting of different materials and design setups, within the scope of embodied and operational energy use. In this direction, it is foreseen that guiding results will be obtained for researchers and designers who want to design sustainable buildings and use prefabricated systems.

2. RESEARCH BACKGROUND

In the article, the master's thesis named "Comparison of Prefabricated Facade Panels According to Their Materials and The Designing Concepts" was used to create prefabricated facade panel scenarios with the wood-based structure that will be examined in terms of embodied carbon and operational energy [22]. It is seen that 16 of the 72 prefabricated facade panels examined within the scope of the thesis have wooden structure material. By examining the design concepts and material combinations of these panels, seven scenarios were created within the scope of this article.

The panel scenarios were applied on a building that reflects the vernacular house characteristics of the Eastern Black Sea Region due to its climate-compatible designs (settle into the topography, orientation, material selection, etc.). In the selection of the sample building, the Ph.D. thesis named “A modeling on the use of a wood-based prefabricated system in the rural settlements in Eastern Black Sea Region” [23] was used. Within the scope of this thesis, 3 vernacular houses reflecting the characteristic features of the Eastern Black Sea Region houses were reinterpreted with Structural Insulated Panels (SIPs) by making use of their proportions.

The structure in which the scenario is applied is the vernacular building no.1 in the thesis. The wooden wall thickness of the selected sample vernacular house is 20 cm, and the stone wall thickness is 50 cm on average. In this direction, in order for the comparison to give accurate results, it was deemed appropriate for all scenarios created to have a total thickness of 20 cm, together with all the materials used in their structures.

The scenarios created within the scope of the study have the necessary parameters to calculate the operational and embodied carbon emissions within the scope of the selected vernacular house building. These parameters are obtained from *Embodied Carbon- The ICE Database V3.0 (2019)* [34] for embodied carbon, from *TS 825 (2008)* [24] sources for operational energy.

3. RESEARCH METHODOLOGY

Although there are many studies on the operational and embodied energy performance of building components made of various materials, there aren't any studies to help designers choose among the various designs of prefabricated wood facade panels that designers have been favoring lately and assess their sustainability.

Within the scope of this study, it aimed to calculate the operational and embodied energy amounts of prefabricated facade panels with different wood-based design concepts by comparing them with the vernacular house facade design, and for this purpose, a sample building was chosen. Scenarios containing 7 different façade concepts were created as an alternative to the façade design of the existing sample building, which is located within the borders of Giresun city in the Eastern Black Sea Region, has a restoration project and the walls forming the façade were built with the Baghdadi construction technique. The facade concepts in these scenarios and the facade design of the vernacular house were compared based on the consumed operational and embodied carbon amounts, and the results were analyzed. Thus, the prefabricated facade panel scenarios were compared regarding sustainability and found the best solution for energy efficiency. *TS 825- Thermal Insulation Rules in Buildings* and *ICE datas* were taken as a reference in the calculations (Figure 1).

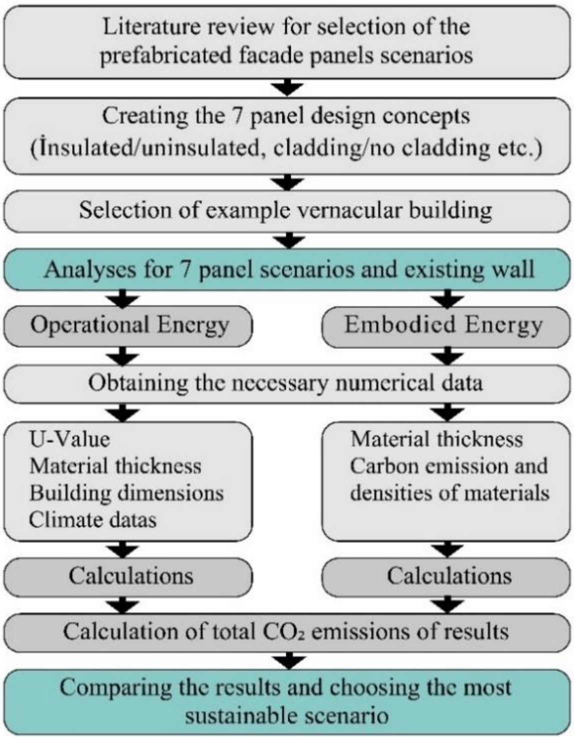

Figure 1. Workflow of the study and methodology

3.1. Example Building and Its Features

İsmail Top House is a vernacular Eastern Black Sea house located in the Demircili neighbourhood of the Epsiye district of Giresun, at an altitude of 150 m, with a construction area of 52.50 m^2 and a building structure system consisting of stone-wood materials. The lower floor of the house is used as a barn (cowhouse); on the upper floor, there are içyanı (meaning interior, including a kitchen), dışyanı (meaning exterior), toilet, living room, and two rooms. The building dimensions are 7.50 x 7.00 m; the height of the first floor is 2.58 m, the height to the roof is 4.88 m, and the total height is approximately 6.5 m [22] (Figure 2).

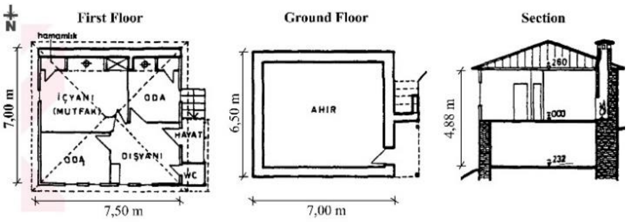

Figure 2. First and ground floor of İsmail Top House and section [25].

All the walls of the building in contact with the ground are made of stone material. It is seen that the first-floor wall of the building facing north is stone and the walls facing other directions are wooden. The stone walls are about 50-60 cm thick, as is the case throughout the region. There are 6 windows and 2 doors in the building. The windows in the building measure approximately 50 x 100 cm and have the traditional ½ ratio. The wooden wall areas of the building were calculated as 50.47 m^2 when window and door spaces are excluded. The total wall area was multiplied by the thickness of the materials included in the foreseen prefabricated facade panel designs, and the amount of use of these materials in the panels is obtained.

3.2. Prefabricated Facade Panels

Prefabricated facade panels are facade components that are produced in panels, can be insulated or uninsulated, coated or uncoated, produced in a factory environment, are one or more storeys high, and are suitable for integrating different materials and systems [22]. Their structure materials can be wood, concrete, metal, and terracotta based. Design setups are classified as massive, sandwich, and frame.

While massive panels are generally produced without insulation, sandwich and frame panels contain thermal insulation material. However, frame panels are suitable for integrating different systems and their performance can be improved with different water, moisture, and vapour membranes (Figure 3).

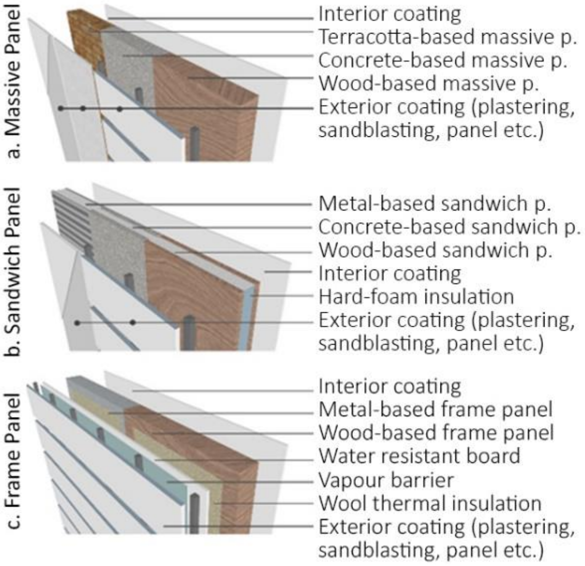

Figure 3. Prefabricated facade panel massive, sandwich and frame designing concepts [26].

In the article, the operational energy and embodied energy of the walls, built with the vernacular wood construction system, are assumed that they are produced with industrial wood-based massive, sandwich and frame prefabricated façade panels, are calculated and presented with comparisons.

3.3. Scenarios

7 scenarios are foreseen as an alternative to the facade of the vernacular sample building discussed in the study. All scenarios have a wood-based structure. While creating the design concepts, different prefabricated facade panel

samples that exist in the literature and are frequently used in the buildings were examined [22]. The walls used in the vernacular house chosen for the study are 20 cm thick. Therefore, the wall thickness has been accepted as 20 cm in all prefabricated facade panel scenarios. In addition, the window and door openings on the facades of the vernacular house were also created in the panels and added to the solar heat gain calculation.

The facade system of the vernacular house, which was chosen as a sample building within the scope of the study, was created with the "Baghdadi technique". This system was built by closing the 10 cm wooden frames on both sides with 2 cm laths and plastering them on both sides with 3 cm plaster (Figure 4).

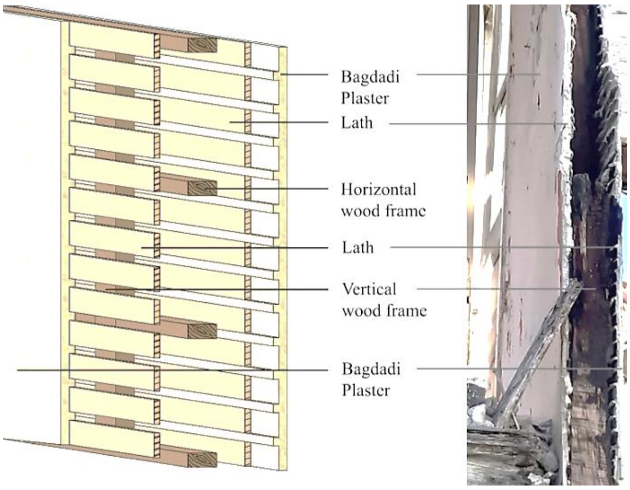

Figure 4. Section of the Baghdadi wall and image of it (*Ayça Akkan archive*)

In the study, as an alternative to the façade system of the sample building, 7 façade scenarios created with 1 massive, 2 sandwich and 4 frame panels are designed as follows (Figure 5) and are summarized in Table 1:

In scenario 1, cross-laminated timber (CLT-Cross Laminated Timber) massive prefabricated facade panel with five layers,

In scenarios 2 and 3, Structural Insulated Panel (SIPs) sandwich prefabricated facade panels with OSB (oriented strand board) in their outer and inner layers; In the middle layers, polyurethane (PUR), in scenario 2, and extruded polystyrene (EPS), in scenario 3, rigid foam thermal insulation layer,

Frame prefabricated facade panel with 18 cm mineral wool insulation in between, covered with OSB and without cladding in scenario 4,

Frame prefabricated facade panel, with 18 cm mineral wool insulation in between, closed with OSB and the outer surface covered with massive spruce wood cladding material, in scenario 5,

In scenario 6, the frame prefabricated facade panel with 18 cm mineral wool insulation between, the inner surface is closed with plasterboard, the outer surface is closed with OSB, the outer surface is covered with massive spruce wood material,

In scenario 7, a prefabricated facade panel, closed with OSB, covered with massive spruce wood material, with 18 cm mineral wool insulation in between, with 0.5 cm vapour Barrier, 0.5 cm waterproofing and 0.5 cm wind barrier, is designed.

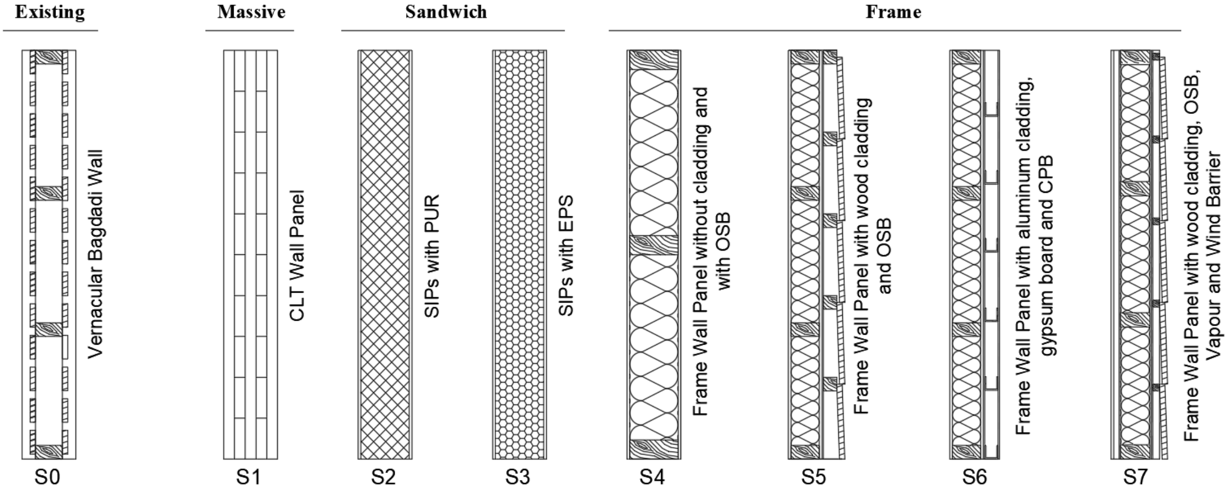

Figure 5. The existing wall and created scenarios (from researchers)

No cladding system was used in scenarios 1,2,3 and 4. It is seen that the panels produced with massive and sandwich design concepts are usually brought to the field without cladding. The cladding process is done on-site and is not included in the prefabrication process. Frame panels, on the other hand, can be produced without cladding but produced generally with cladding. For this reason, just one unclad frame panel design (S4) is preferred.

Table 1. The existing building wall system and the design concepts of the proposed scenarios

Scenario	Layers	Materials with thickness
Scenario 0: Traditional Blacksea House in Giresun, Epsiye.	***Interior Covering***	***3 cm Baghdadi plaster***
	Main Structure	***2 cm Baghdadi Lath*** ***10 cm Wood frame*** ***2 cm Baghdadi Lath***
	Exterior Covering	***3 cm Baghdadi plaster***
Scenario 1: Massive facade panel	Main Structure	20 cm CLT
Scenario 2: Sandwich facade panel with PUR core	Main Structure	20 cm SIP with PUR (1 OSB +18+1 OSB)
Scenario 3: Sandwich facade panel with EPS core	Main Structure	20 cm SIP with EPS (1 OSB +18+1 OSB)
Scenario 4: Frame facade panel without cladding, with OSB	Interior Covering	1 cm OSB
	Main Structure	18 cm Wood frame 18 cm Mineral Wool
	Exterior Covering	1 cm OSB
Scenario 5: Frame facade panel with cladding, with OSB	Interior Covering	1 cm OSB
	Main Structure	10.5 cm Wood frame 10.5 cm Mineral Wool
	Exterior Covering	1 cm OSB 0.5 cm Waterproofing 5 cm Lath 2 cm Wood cladding
Scenario 6: Frame facade panel with Aluminum cladding, gypsum board and cement particle board	Interior Covering	1 cm Gypsum board
	Main Structure	13 cm Wood frame 13 cm Mineral Wool
	Exterior Covering	1 cm Cement particle board (CPB) 0.5 cm Waterproofing 5 cm Al. Profile (1 cm total thickness) 0.5 cm Al. sheet
Scenario 7: Frame facade panel with cladding, with OSB, with Vapor and Wind Barrier	Interior Covering	1 cm OSB 2 cm Lath (with air) 0.5 cm Vapor Barrier
	Main Structure	10 cm Wood frame 10 cm Mineral Wool
	Exterior Covering	1 cm OSB 0.5 cm Waterproofing 0.5 cm Wind barrier 2.5 cm Lath 2 cm Wood cladding

3.4. Calculation of and Data for Embodied Energy

Embodied energy is the energy a building uses throughout its life cycle. A building's first use of embodied energy occurs during the manufacture and transportation of products and the building's construction. Maintaining the building, repairing, and replacing damaged materials and components repeat the use of embodied energy. The end embodied energy use occurs during the destruction stage, which is the final stage of the life cycle. Destroying the building, recycling components and transporting waste cause the use of embodied energy [27]. Especially since the consumption of non-renewable energy sources will increase CO_2 emissions, the damage to the environment is also increasing. In this direction, a return to vernacular architecture has begun [28].

The choice of material and construction system are among the factors that affect the building's embodied energy use. Facades, that provide interior comfort by protecting the building like a shell, are among the building elements that affect energy conservation. Therefore, the embodied energies of the materials used in the facade design are important. At the same time, a prefabricated construction system can be also preferred to obtain an optimum result. Abey and Anand [29] examined two different construction systems, conventional and prefabricated, in terms of embodied energy, in their research on a typical reinforced concrete apartment project. As a result of this study, it was emphasized that there is a 90% material share in the building embodied energy. The share of prefabricated building elements in embodied energy is 5% due to the distance from the shipping point and 3% in the traditional structure. Human labour plays a role of 0.86% in prefabricated buildings and 2.5% in the traditional structure. In addition, it is seen that the use of wall materials such as bricks in prefabricated structures increases embodied energy.

The embodied carbon values and thermal conductivity values, calculated for the prefabricated facade panel scenarios created within the scope of this study, were obtained from the *"Inventory of Carbon & Energy"* [34]. Other sources were used for the data that could not be obtained (Table 2).

3.5. Calculation of and Data for Operational Energy

Operational energy can be defined as the energy that results from the daily use of the building. In order to reduce the operating energy, the energy demand for uses such as electricity, heating-cooling, ventilation, and water-heating should be reduced [30].

Table 2. The data received from the ICE

	Embodied Carbon $kgCO_{2e}/kg$	Thermal Conductivity W/mK	Density kg/m^3
Bagdadi plaster (plaster)	0.13	0.30[27]	1400
Bagdadi Lath (softwood)	0.26	0.13	600
Wood frame (hardwood)	0.81	0.12	510
CLT	0.44	0.15	650
Lath (softwood)	0.26	0.12	510
Wood clad. (hardwood)	0.81	0.12	510
OSB	0.45	0.098	750
CPB	0.55	0.080	350
Alu. profile	8.781	204	2700
Alu. sheet	5.545	204	2700
Gypsum (plasterboard)	0.39	0.25[23]	800
PUR	4.26	0.025[23]	30
EPS	3.26	0.035[23]	30
Mineral Wool	1.28	0.035[23]	50
Waterproofing (polyethylene)	2.54	0.19[23]	1000
Vapour Bar. (polystyrene)	3.29	0.035[23]	1200
Wind bar. (polypropylene	4.49	0.30[23]	900

Besides these uses, the energy source has a critical role. If it is used the source released high greenhouse gas emissions, which will be disadvantageous for energy efficiency. The renovation is made with some insulation materials and windows with high performance, which can provide energy efficiency, but these materials result in greenhouse gas emissions during production [31].

Reducing the heating requirement in residential buildings is the first method for using energy effectively. In this direction, the thermal insulation materials and their thicknesses to be used are important. Especially the rapid depletion of fossil fuels and problems such as global warming have made thermal insulation more significant [32].

The annual heating energy requirement demands were calculated according to the *TS 825 Standard of Thermal Insulation Requirements for Buildings* [24] to acquire the operational energy use. Therefore U-values of the designed panels in this study are significant because affect the facade performance. So, the U-values were calculated in the first phase, then the energy consumption was obtained using the calculation method. Finally, the energy consumption, which was calculated as joule, was translated to kilowatt (1kJ=0.278 x 10^{-3}kWh) and multiplied by 0.88 for calculating the carbon dioxide per kilowatt hour by using Eq. 1 [33].

$$U = \frac{1}{R_1+R_2+R_3+\cdots R_s} \quad (1)$$

After calculating the panel U-values, the annual energy requirements of the single-volume building for the panels integrated into the building are calculated with Eq. 2 and 3.

$$Q_{year} = \sum Q_{month} \quad (2)$$

$$Q_{month} = [H(\theta_i - \theta_e) - \eta_m(\phi_{i.month} + \phi_{s.month})].t \quad (3)$$

There are six windows on the upper floor where the prefabricated facade panels will be located, the scenario of which has been prepared. Four windows are located on the south façade, one on the west façade and the last window on the east façade. In this direction, the monthly average solar heat gain was calculated by using Eq. 4 [24].

$$\phi_{s.m} = \sum \mathrm{ri, month\ x\ gi, month\ x\ Ii, month\ x\ Ai} \quad (4)$$

For the monthly average shading factor of transparent surfaces, which is expressed as ri, month in equation 4, the value of 0.8, signified in TS825, for discrete and low-rise buildings is used. Also, the gi, month value, which is the solar transmission factor, was calculated as 0.68, assuming that a single clear glass was used. The monthly solar radiation intensity on the vertical surfaces Ii, month was calculated according to the months one by one and the average value obtained was 127,39 W/m^2. The total window area Ai is 3 m^2. The monthly average internal gain $\phi_{i.m}$ was calculated as 593,352 W/m^2. It was used Equations 5 and 6 for calculating the gains utilization factor.

$$\eta_{month} = 1 - e^{(-1/KKO_{month})} \quad (5)$$

$$KKO_{month} = (\phi_{i.month} + \phi_{s.month})/\mathrm{H}(\theta_i - \theta_e) \quad (6)$$

In order to obtain the specific heat loss of the building with the symbol H the inequality in Eq. 7, is used.

$$\mathrm{H} = \mathrm{H}_t + \mathrm{H}_v \quad (7)$$

The following equation is used to calculate the H_t value. The U_I value representing the linear transmittance of the thermal bridge is ignored.

$$\mathrm{H}_t = \sum \mathrm{AU} + |\mathrm{U_I} \quad (8)$$

$$\sum \mathrm{AU} = \mathrm{U_D A_D + U_P A_P + U_k A_k} + 0.8\ \mathrm{U_T A_T} + 0.5\ \mathrm{U_t A_t + U_d A_d} + 0.5\mathrm{U_{ds} A_{ds}} \quad (9)$$

The study aims to examine the effect of these 7 prefabricated facade panels and the existing building wall on the annual energy requirement of the building. Therefore, the exterior door (A_k), ceiling (A_T), floor sitting on the ground (A_t), the floor in contact with the outside air (A_d) and structural elements (A_{ds}) in contact with the indoor environment at low temperatures are not considered in the equation. However, the window area (A_p) was calculated as 3 m^2 and the U_p value of the windows was obtained as 5.1 W/m^2K from TS 825.

It is assumed that HVAC systems are not used in the building and the spaces are only ventilated with natural ventilation. In this direction, the heat loss (H_v) that will occur as a result of natural ventilation is calculated with equation 10.

$$\mathrm{H}_v = \rho.c.V^i = \rho.c.\mathrm{n}_h.\mathrm{V}_h = 0.33\ .\mathrm{n}_h.\mathrm{V}_h \quad (10)$$

The annual energy requirement and operational carbon obtained as a result of the calculations are given under the title of "operational energy use".

4. RESULTS AND DISCUSSION

4.1. Embodied Energy Use

The density, total usage, and embodied carbon amounts per kilogram of the materials included in the existing wall system and the prefabricated facade panel scenarios brought as suggestions are required for the total embodied carbon calculation. Therefore, the data obtained as a result of the calculations made in line with the values obtained within the scope of ICE are shown in Table 2.

Among the 8 scenarios, the existing wall system (S0) ranks third in terms of carbon emissions with 2221.3926 kgCO$_{2e}$/kg. The embodied carbon of the S6, which is in the last place and has an aluminium outer cladding system, is 5647.778766 kgCO$_{2e}$/kg. The best-embodied carbon result (minimum) was obtained with SIPs using PUR in S3, with 2136.93228 kgCO$_{2e}$/kg. This panel scenario is followed by S2, S0, S4, S5, S7 and S6.

Considering S0, S4 and S5, it is seen that the wooden frame used as a structure, one of the materials within the panel, has a large proportion of carbon emissions. However, in the S6, which has the same wooden structure system, aluminium materials; In S7, on the other hand, the embodied carbon of the membrane insulation elements is higher than the materials in the overall panel. In S2 and S3, which are panel scenarios with sandwich panel design, it is seen that rigid foam insulations have 77% and 72% embodied carbon ratios. Therefore, it can be concluded that petroleum, plastic, and metal-based building materials play an effective role in the embodied carbon ratio. It is noteworthy that the embodied carbon values of S0 produced with traditional methods and local materials are lower than the other four scenarios (S4, S5, S6, and S7) (Table 3). It was seen that the panel structure system constitutes 58% of the total carbon emissions. The wood materials in the panels caused about 51% of embodied energy and, thermal insulation materials are about 31%.

Table 3. Embodied energy and carbon of prefabricated facade panel scenarios

	Total Usage (m^3)	Density (kg/m^3)	Mass (kg)	Embodied Carbon (kgCO$_{2e}$/kg)	Total Embodied Carbon (kgCO$_{2e}$/kg)	Material percentage embodied carbon
Scenario 0					**2221.3926**	
Bagdadi plaster	4.3092	1400	6032.88	0.13	784.2744	35%
Bagdadi Lath	2.8728	600	1723.68	0.26	448.1568	20%
Wood frame	2.394	510	1220.94	0.81	988.9614	**45%**
Scenario 1					**4108.104**	
CLT	14.364	650	9336.6	0.44	4108.104	**100%**
Scenario 2					**2136.93228**	
OSB	1.4364	750	1077.3	0.45	484.785	23%
PUR	12.9276	30	387.828	4.26	1652.14728	**77%**
Scenario 3					**1749.10428**	
OSB	1.4364	750	1077.3	0.45	484.785	28%
EPS	12.9276	30	387.828	3.26	1264.31928	**72%**
Scenario 4					**2816.49312**	
OSB	1.4364	750	1077.3	0.45	484.785	17%
Wood frame	4.3092	510	2197.692	0.81	1780.13052	**63%**
Mineral Wool	8.6184	50	430.92	1.28	551.5776	20%
Scenario 5					**3445.67223**	
OSB	1.4364	750	1077.3	0.45	484.785	14%
Wood frame	2.5137	510	1281.987	0.81	1038.40947	**30%**
Mineral Wool	5.0274	50	251.37	1.28	321.7536	9%
Lath	0.7182	510	366.282	0.26	95.23332	3%
Waterproofing	0.3591	1000	359.1	2.54	912.114	26%
Wood cladding	1.4364	510	732.564	0.81	593.37684	17%
Scenario 6					**11741.24612**	
Gypsum	0.7182	800	574.56	0.39	224.0784	2%
Wood frame	3.1122	510	1587.222	0.81	1285.64982	11%
Mineral Wool	6.2244	50	311.22	1.28	398.3616	3%
CPB	0.7182	350	251.37	0.554	139.25898	1%
Alu. Profile	0.14364	2700	387.828	8.781	3405.517668	29%
Waterproofing	0.3591	1000	359.1	2.54	912.114	8%
Alu. Sheet	0.3591	2700	969.57	5.545	5376.26565	**46%**
Scenario 7					**6240.229128**	
OSB	1.4364	750	1077.3	0.45	484.785	8%
Lath	0.64638	510	329.6538	0.26	85.709988	1%
Vapour Barrier	0.3591	1200	430.92	3.29	1417.7268	23%
Wood frame	2.394	510	1220.94	0.81	988.9614	16%
Mineral Wool	4.788	50	239.4	1.28	306.432	5%
Waterproofing	0.3591	1000	359.1	2.54	912.114	15%
Wind barrier	0.3591	900	323.19	4.49	1451.1231	**23%**
Wood cladding	1.4364	510	732.564	0.81	593.37684	10%

4.2. Operational Energy Use

In order to obtain the annual operational energy and carbon consumed by a building, parameters such as the thermal transmittance coefficient of the building envelope and building dimensions are needed. In addition, the openings in the building envelope, which is open to external environmental conditions, and the building elements that enable sunlight to be used, such as windows, are important.

The thermal transmittance coefficients (U-Value) calculated for the eight scenarios created within the scope of the study are given in Table 4. U-values are low for S0 and S1 which do not include any insulation material; It is seen that the other panels provide the minimum U value (0.60 W/m^{2}K) stipulated for the 2nd Climate Region in TS825. However, S2 with a sandwich panel concept with 18 cm PUR thermal insulation material gave the best thermal insulation result (Table 4).

Table 4. The thermal conductivity and transmittance coefficients of the scenarios

	R-Value	U-Value (W/m^{2}K)
Scenario 0	0.968132	0.88
Scenario 1	1.333333	0.67
Scenario 2	7.404082	0.13
Scenario 3	5.346939	0.18
Scenario 4	5.346939	0.18
Scenario 5	3.754207	0.25
Scenario 6	3.630125	0.18
Scenario 7	2.544683	0.26

It is seen that the U-values of the scenarios that contain more structural elements among the panels designed with the same thicknesses decrease as the thickness of the structural element and thermal insulation materials decreases. The calculation example made to compare the annual heating requirement and the released carbon data for prefabricated facade panels and the vernacular wall is given in Table 6 and 7 for scenario 7.

In the annual heat requirement calculation, S2 with a high U-value panel is seen as the scenario with the least annual heat requirement and accordingly the lowest operational carbon. In scenarios 0 and 1, which do not contain any insulation material, it is concluded that the annual heat requirement is higher than in the other scenarios and carbon emissions are higher in this direction (Table 5).

In comparison with scenario 0, it is obtained that S1 among the designed prefabricated facade panel scenarios provides the lowest energy savings with a rate of 15.91%. Although, S2 is the most energy-saving design with a rate of 53.21%. Also, it has been seen that S3-S4-S6, S5 and S7 provide energy efficiency of %50.02, 45.46% and 44.79% respectively.

Table 5. The effect of prefabricated facade panel scenarios on annual heat requirement and operational energy

	H	J	Wh	CO_{2e}
S0	141.52	13792726620	3834378	3374.253
S1	126.44	11598302930	3224328	2837.409
S2	87.66	6453632900	1794110	1578.817
S3	91.25	6893320000	1916343	1686.382
S4	91.25	6893320000	1916343	1686.382
S5	96.28	7523047070	2091407	1840.438
S6	91.25	6893320000	1916343	1686.382
S7	97.00	7614304660	2116777	1862.763

Considering the annual heat requirement and carbon emissions obtained in Table 5, the order of best to worst scenarios in terms of energy efficiency is S2, S6-S3-S4, S5, S7, S1 and S0 (Figure 6).

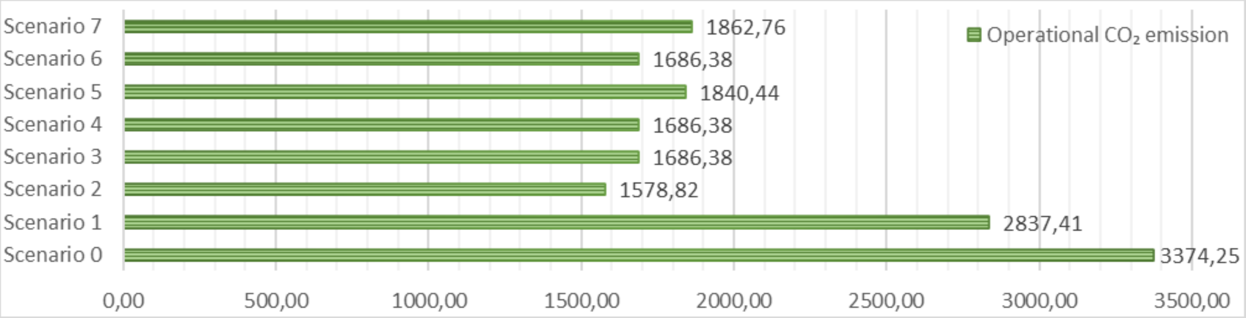

Figure 6. Operational carbon comparison of scenario

Table 6. The example table of the annual energy requirements of scenario 7 ($Q_{month} = [H(\theta_i - \theta_e) - \eta_{month}(\phi_{i.month} + \phi_{s.month})].t$)

	Heat Losses			**Heat Gains**							
Months	$\boldsymbol{\theta_e}$	$\boldsymbol{\theta_i - \theta_e}$	**Heat loss H($\boldsymbol{\theta_i - \theta_e}$)**	**Solar gains $\boldsymbol{\phi_s}$**	**Total gains $\boldsymbol{\phi_t}$**	**KKO**	$\boldsymbol{\eta_{month}}$	**t**	**Heating energy requirement $\boldsymbol{Q_{month}}$ (J)**	**Wh**	$\boldsymbol{CO_{2e}}$
	2.9	16.1	1561.6	97.1	690.46	0.4421	0.8958	2592000	2444511404	679574	598.0252
February	4.4	14.6	1416.1	116.9	807.42	0.5702	0.8269	2592000	1940062053	539337	474.6167
March	7.3	11.7	1134.8	129.7	937.16	0.8258	0.7021	2592000	1236082944	343631	302.3953
April	12.8	6.2	601.4	140.4	1077.5	1.7918	0.4277	2592000	364197894.7	101247	89.09737
May	18	1	97.0	152.6	1230.1	12.682	0.0758	2592000	9656675.038	0	0
June	22.5	0	0.0	159.1	1389.2	0.0000	0.0000	2592000	0	0	0
July	24.9	0	0.0	155.3	1544.5	0.0000	0.0000	2592000	0	0	0
August	24.3	0	0.0	149.9	1694.4	0.0000	0.0000	2592000	0	0	0
September	19.9	0	0.0	134.4	1828.8	0.0000	0.0000	2592000	0	0	0
October	14.1	4.9	475.3	116.1	1944.9	4.0922	0.2168	2592000	138974923.5	0	0
November	8.5	10.5	1018.5	91.4	2036.3	1.9994	0.3936	2592000	562586118.4	156399	137.6310
December	3.8	15.2	1474.3	85.7	2121.9	1.4393	0.5008	2592000	1066864244	296588	260.9976
									Q_{year}=∑Q_m	2116777	1862.763

* The values are as follows: H = 97, θ_i = 19, and ϕ_i (Internal Heat Gain) = 593.352

**If the KKO is 2.5 and above. the heating energy requirement is taken as zero.

Table 7. The calculation of the annual total solar gains obtained from windows

Months	**South**					**North**					**West/East**					**Total solar gains**
	r	**g**	**I**	**A**	$\boldsymbol{\phi_s}$	**r**	**g**	**I**	**A**	$\boldsymbol{\phi_s}$	**r**	**g**	**I**	**A**	$\boldsymbol{\phi_s}$	$\boldsymbol{\phi_{s.top.}}$
January	0,8	0,68	72	2	78,336	0,8	0,68	26	0,5	7,072	0,8	0,68	43	0,5	11,696	97,104
February	0,8	0,68	84	2	91,392	0,8	0,68	37	0,5	10,064	0,8	0,68	57	0,5	15,504	116,96
March	0,8	0,68	87	2	94,656	0,8	0,68	52	0,5	14,144	0,8	0,68	77	0,5	20,944	129,744
April	0,8	0,68	90	2	97,92	0,8	0,68	66	0,5	17,952	0,8	0,68	90	0,5	24,48	140,352
May	0,8	0,68	92	2	100,096	0,8	0,68	79	0,5	21,488	0,8	0,68	114	0,5	31,008	152,592
June	0,8	0,68	95	2	103,36	0,8	0,68	83	0,5	22,576	0,8	0,68	122	0,5	33,184	159,12
July	0,8	0,68	93	2	101,184	0,8	0,68	81	0,5	22,032	0,8	0,68	118	0,5	32,096	155,312
August	0,8	0,68	93	2	101,184	0,8	0,68	73	0,5	19,856	0,8	0,68	106	0,5	28,832	149,872
September	0,8	0,68	89	2	96,832	0,8	0,68	57	0,5	15,504	0,8	0,68	81	0,5	22,032	134,368
October	0,8	0,68	82	2	89,216	0,8	0,68	40	0,5	10,88	0,8	0,68	59	0,5	16,048	116,144
November	0,8	0,68	67	2	72,896	0,8	0,68	27	0,5	7,344	0,8	0,68	41	0,5	11,152	91,392
December	0,8	0,68	64	2	69,632	0,8	0,68	22	0,5	5,984	0,8	0,68	37	0,5	10,064	85,68

Considering the operational and embodied carbon energy obtained for 8 scenarios within the scope of the study; It is seen that the total amount of emissions is mostly caused by embodied energy. However, in scenarios created without an insulating material, operational energy, and operational carbon are high because the thermal transmittance coefficient is low. It is seen that the CLT wood-based element used in scenario 1 causes more carbon emissions than the natural wood materials used in other scenarios. While the embodied carbon ratio of scenario 6 where metal-based materials are used is higher than the operational carbon; It was concluded that scenario 3 with the EPS insulation and OSB, has the lowest embodied carbon ratio (Figure 7).

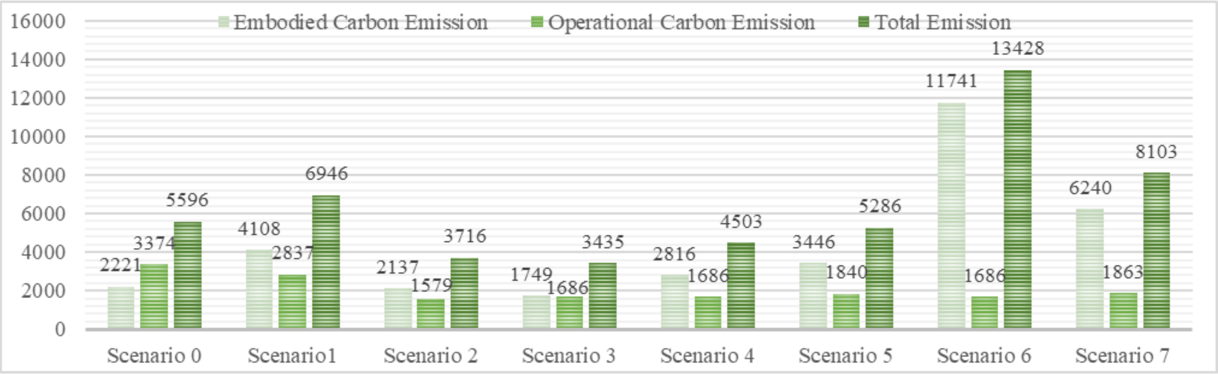

Figure 7. Impact of embodied and operational carbon on total carbon emission

Figure 8 shows the contribution of operational and embodied carbon emissions to total carbon emissions. In general, it can be said that embodied carbon emissions are more effective. However, although the carbon emission originating from the material is low in the Baghdadi wall type, where local materials are used, the operational carbon emission originating from heating and cooling is high due to the insufficient thermal performance of the panel. In addition, it is seen that operational and embodied energy emission rates are at their closest values in Scenario 3.

In Scenario 6, however, there is a significant difference in the rate of embodied carbon emission originating from the material compared to the operational carbon emission amount. In this respect, it is necessary to emphasize the contribution of metal-based elements used in the scenario.

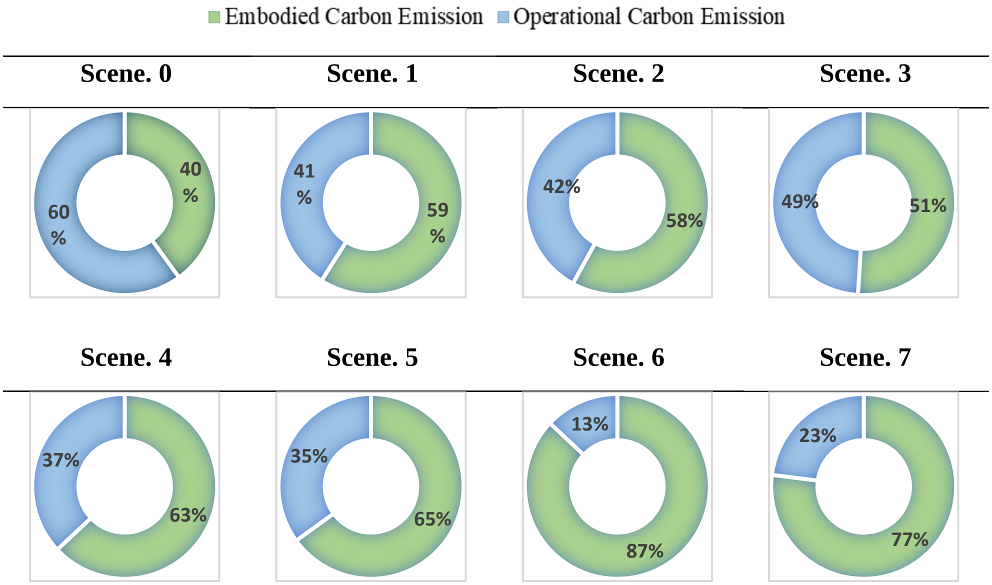

Figure 8. The ratio of embodied and operational carbon on total carbon emissions

When the final total amount of carbon produced by the scenarios is examined, it is shown that scenario 3 is the most sustainable and the least and scenario 6 has the highest carbon emission. However, it was concluded that the insulation materials such as water, moisture and vapour control materials added to the panel and the metal-based cladding system used instead of the ventilated wood cladding system adversely affected the embodied carbon.

5. CONCLUSIONS

The vernacular architecture in the Eastern Black Sea region is important both for our cultural life and for a sustainable environment. However, indoor comfort may be insufficient due to the limits of opportunities and the structures produced using materials situated in the near environment. Therefore, various materials or systems can be proposed to strengthen vernacular or old structures-facades and to be used in new structures.

Prefabricated systems increase the speed of work at the construction site and reduce the need for manpower. However, the rapid construction process helps the building to be affected by the environmental conditions least. Sustainability, lightness, and resistance to lateral loads are important criteria for the selection of prefabricated structural systems, especially those made of wooden material. Prefabricated facade panels are facade components that can close all kinds of building facades, regardless of the construction system and building material. These panels, whose structure system can be produced from wood, concrete, metal or terracotta materials, can perform well with the insulation materials they contain.

Within the scope of this study, wooden-based prefabricated facade panel scenarios that can be suggested for Eastern Black Sea regional vernacular buildings with a Baghdadi wall system were created as the alternative. These panels were analyzed in terms of embodied and operational energy and compared with the existing vernacular wall system.

As a result of the study, the vernacular Baghdadi wall has the lowest embodied carbon emission at 40%, while the frame panel in Scene 6—which comprises metal-based elements—has the greatest embodied carbon emission at 87%. Additionally, the CLT massive wood panel (Scene.1) was the least energy-efficient scenario with 15.9%, while the sandwich panel with PUR insulation material was the most energy-efficient scenario with 53.21%.

Considering the embodied and operational carbon emissions produced by the panels, it can be said that the sandwich panel design concept is more energy efficient and sustainable because it contains less material and thicker thermal insulation elements. In addition, it has been determined that the operational energy use and the produced amount of operational carbon increase in the wooden frame and thermal insulation scenarios whose thickness is gradually decreasing. Considering that not only the thermal insulation performance of the facade panels but also the performance properties such as water and sound insulation and fire resistance should strengthen the ability of frame panels to supply different performance requirements should be considered in the design concept. It is noteworthy that uninsulated massive panels alone cannot supply the required performance requirement.

This study, which examines prefabricated facade panels in terms of operational and embodied energy, can also be developed by adding other criteria such as condensation and acoustic performance properties.

DECLARATION OF ETHICAL STANDARDS

The authors of this article declare that the materials and methods they use in their studies do not require ethics committee permission and/or legal-specific permission.

AUTHORS' CONTRIBUTIONS

Ayça AKKAN ÇAVDAR: contributed to the research idea, writing, data analysis, and graph making.

Nilhan VURAL: participated in the concept design, review, and editing of the article.

CONFLICT OF INTEREST

There is no conflict of interest in this study.

REFERENCES

[1] Kolodiy, O., & Capeluto, G. "Towards zero-energy residential complexes in high-density conditions". ***Indoor and Built Environment,*** 30(10), 1751-1765, (2021).

[2] EUM. "Building Industry Energy Efficiency Technology Atlas", January, Ankara. https://webdosya.csb.gov.tr/db/meslekihizmetler/icerikler/atlas_ocak_small-20210126120540.pdf (2021, accessed 15 January 2023).

[3] MEUCC. "By-Law on Energy Performance of Building", (2008)

[4] Turkish Statistical Institute (TUIK). "Total greenhouse gas emissions by sector 1990-2020". available at https://data.tuik.gov.tr/Bulten/DownloadIstatistikselTablo?p=enT0SQ56KzCA/fsTjUVcTJGfPQM4h2UFlSnOHMzolXDHlPHrrJFY2ifBcwT4ak8m (2022, accessed 15 January 2023).

[5] Önder, H. G. "Renewable energy consumption policy in Turkey: An energy extended input-output analysis". ***Renewable Energy,*** 175, 783–796, (2021).

[6] Usta, P., & Zengin, B. "The Energy Impact of Building Materials in Residential Buildings in Turkey". ***Materials,*** 14(11), 2793, (2021).

[7] Demirsoy, G. & Sözen, A. "Binalarda Enerji Verimliliğinin Toplam Faktör Etkinliği". ***Politeknik Dergisi***, 1-1, (2022).

[8] Sartori, T., Drogemuller, R., Omrani, S., & Lamari, F. "A schematic framework for Life Cycle Assessment (LCA) and Green Building Rating System (GBRS)". ***Journal of Building Engineering***, 38, 102180, (2021).

[9] Figueiredo, K., Pierott, R., Hammad, A. W. A., & Haddad, A. "Sustainable material choice for construction projects: A Life Cycle Sustainability Assessment framework based on BIM and Fuzzy-AHP". ***Building and Environment***, 196, 107805, (2021).

[10] Merritt, F. S., & Ricketts, J. T. "Building design and construction handbook". ***McGraw-Hill Education***, (2001).

[11] Pan, W., Iturralde, K., Bock, T., Martinez, R. G., Juez, O. M., & Finocchiaro, P. A "Conceptual Design of an Integrated Façade System to Reduce Embodied Energy in Residential Buildings". ***Sustainability***, 12(14), 5730, (2020).

[12] Koezjakov, A., Urge-Vorsatz, D., Crijns-Graus, W., & Van den Broek, M. "The relationship between operational energy demand and embodied energy in Dutch residential buildings". ***Energy and Buildings,*** 165, 233-245, (2018).

[13] Lolli, N., Fufa, S. M., & Inman, M. "A parametric tool for the assessment of operational energy use, embodied energy and embodied material emissions in the building". ***Energy Procedia***, 111, 21-30, (2017).

[14] Iddon, C. R., & Firth, S. K. "Embodied and operational energy for new-build housing: A case study of

construction methods in the UK". ***Energy and Buildings***, 67, 479-488, (2013).

[15] Yang, Q., & Li, N. "Optimal design of residential balcony based on environmental benefit: A case study in hot summer and cold winter area of China". ***Indoor and Built Environment***, 0(0), 1-13, (2022).

[16] Hammond, G., & Jones, C. "Inventory of carbon & energy: ICE (Vol. 5)". Bath: Sustainable Energy Research Team, Department of Mechanical Engineering, ***University of Bath***, (2008).

[17] Zeitz, A., Griffin, C. T., & Dusicka, P. "Comparing the embodied carbon and energy of a mass timber structure system to typical steel and concrete alternatives for parking garages". ***Energy and Buildings***, 199, 126-133, (2019).

[18] Rodrigues, V., Martins, A. A., Nunes, M. I., Quintas, A., Mata, T. M., & Caetano, N. S. "LCA of constructing an industrial building: Focus on embodied carbon and energy". ***Energy Procedia,*** 153, 420-425, (2018).

[19] Yıldırım, E. "The evaluation of environmental sustainability in the context of operational and embodied energy on exterior wall, examples of hotel buildings from Istanbul", ***Master's Thesis***, İstanbul Technical University, Graduate Institute of Natural and Applied Sciences, İstanbul, (2018).

[20] Lupíšek, A., Nehasilová, M., Mančík, Š., Železná, J., Růžička, J., Fiala, C., … Hájek, P. "Design strategies for buildings with low embodied energy". ***Proceedings of the Institution of Civil Engineers - Engineering Sustainability***, 170(2), 65–80, (2017).

[21] Zhang, T., Zhong, W., & Yu, C. W. "Energy agenda of architectural formation: To progress sustainable built environment through the approach of energy-driven architectural formation". ***Indoor and Built Environment,*** 30(10), 1591-1595, (2021).

[22] Akkan, A. "Comparison of prefabricated facade panels according to their materials and design concepts" (Hazır cephe panellerinin malzemelerine ve tasarım kurgu özelliklerine göre karşılaştırılması), ***Master's Thesis,*** Karadeniz Technical University, Graduate Institute of Natural and Applied Sciences, Trabzon, (2020).

[23] Vural, N. "A model on the use of wood-based prefabricated systems in rural settlements in the Eastern Black Sea region". (Doğu Karadeniz bölgesi kırsal yerleşmelerinde ahşap esaslı prefabrike sistem kullanımı üzerine bir modelleme), ***Ph.D Thesis,*** Karadeniz Technical University, Graduate Institute of Natural and Applied Sciences, Trabzon, (2006).

[24] TS 825. "Standard of Thermal Insulation Requirements for Buildings", (2008).

[25] Sümerkan, M. R. "Building characteristics of the traditional houses in respect to the shaping factors at eastern black sea region", ***Ph.D. Thesis,*** Karadeniz Technical University, Graduate Institute of Natural and Applied Sciences, Trabzon, (1990).

[26] Akkan, A. & Vural, N. "Thermal, sound and fire performance properties of prefabricated facade panels with massive, sandwich and frame design concepts". ***Journal of Architectural Sciences and Applications***, 7(1), 464-481, (2022).

[27] Singh, M. K., Mahapatra, S., & Atreya, S. K. "Solar passive features in the vernacular architecture of North-East India". ***Solar Energy***, 85(9), (2011).

[28] Işık, A. B. "Cumalıkızık'ta yeniden hımış yapı", ***3.Bin Yılda Osmanlı Köyü: Cumalıkızık Sempozyumu***, Bursa Yıldırım Belediyesi, Bursa Mimarlar Odası, Barış Manço Kültür Merkezi, Bursa, (2007).

[29] Abey, S. T., & Anand, K. B. "Embodied energy comparison of prefabricated and conventional building construction". ***Journal of The Institution of Engineers (India): Series A***, 100(4), 777-790, (2019).

[30] Anderson, J. E., Wulfhorst, G., & Lang, W. "Energy analysis of the built environment—A review and outlook". ***Renewable and Sustainable Energy Reviews,*** 44, 149-158, (2015).

[31] Aydın, N. & Bıyıkoğlu, A. "Türkiye'de Konut Tipi Binaların Isıtma Yükü Altında Ömür Maliyet Analizi Yöntemi ile Optimum Yalıtım Kalınlıklarının Belirlenmesi" ***Politeknik Dergisi,*** 22 (4), 901-911, (2019).

[32] Allende, A. L., & Stephan, A. "Life cycle embodied, operational and mobility-related energy and greenhouse gas emissions analysis of a green development in Melbourne, Australia". ***Applied Energy***, 305, 117886, (2022).

[33] Gong, X., Nie, Z., Wang, Z., Cui, S., Gao, F., & Zuo, T. "Life Cycle Energy Consumption and Carbon Dioxide Emission of Residential Building Designs in Beijing". ***Journal of Industrial Ecology,*** 16(4), 576–587, (2012).

[34] Embodied Carbon- "The ICE Database V3.0". https://circularecology.com/embodied-carbon-footprint-database.html (2019, accessed 17 January 2022).