IMPROVING THE ENERGY EFFICIENCY OF PORT FACILITIES AND THEIR SUSTAINABLE DEVELOPMENT USING SOLAR ENERGY: EVIDENCE FROM ROMANIA

Laura-Alexandra DOROFTEI (1), Gheorghe MILITARU (2)

(1) Industrial Engineering (PhD), Faculty of Entrepreneurship, Business Engineering and Management, National University of Science and Technology POLITEHNICA of Bucharest, Romania, e-mail: lauradoroftei10@gmail.com

(2) Business Engineering and Management, Faculty of Entrepreneurship, Business Engineering and Management, National University of Science and Technology POLITEHNICA of Bucharest, Romania, e-mail: gheorghe.militaru@upb.ro

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1. **ABSTRACT:** The purpose of this paper is to find solutions for improving the energy efficiency of port facilities and operations to reduce carbon footprint and achieve sustainable development. Ports are important gateways for international commerce, and they are a vital part of the global transportation network. However, there is a notable deficiency in terms of improving energy efficiency and integrating renewable energy into port facilities and operations. It is found that port authorities in the maritime domain face major challenges in reducing electricity consumption and carbon footprint by supporting increased resilience and energy efficiency. This study provides solutions for port authorities regarding the implementation of solutions to increase the energy efficiency of port buildings. This paper aims to summarize the application of EDGE platform to identify different solutions using photovoltaic panels and different measures that were simulated with the aim of improving the energy efficiency of the port facilities. The data and model used targeted the port of Constanta in Romania. The use of solar energy as a renewable energy source for the port of Constanta is based on the location of this facility in an area with high solar radiation. The research results indicate a payback of the investment from the revenues generated from the sale of energy produced by the PV plant in less than 9 years and a carbon footprint reduction of 197.2 tCO_2 /year. The use of batteries for electrical energy storage contributes significantly to a better integration of renewable sources in port facilities and operations. The research results show that there is great potential for ports to increase the energy efficiency of their facilities and operations, offering such future research opportunities.

2. INTRODUCTION

Since their beginnings, ports have been and still are a vital part of maritime transportation, together forming a global network that enables the exchange of goods and the transportation of passengers anywhere in the world. Since ports are responsible for 80% of world trade, they are very important for good economic development. According to research, the shipping sector is responsible for about 11% of greenhouse gas emissions [1]. Port activities and operations are energy intensive and rely heavily on fossil fuels. The use of renewable energy is therefore essential to increase sustainability and reduce emissions. Methods for integrating renewable energy resources are diverse and include hybridization and optimization of systems, integration of storage and development of energy communities [2]. A flexible and efficient energy management system can reduce the challenges caused by high energy demands. To cope with these demands, large capacity storage systems are preferred. Renewable polygeneration systems are cost-effective and the benefits in terms of environmental impact are remarkable. Ships docked in ports are responsible for emissions of SOx, NOx and PM2.5 [3]. Thanks to their energy production, which uses renewable energy technologies, ports can also reduce these emissions. This is achieved by connecting the ship's equipment to the port's renewable energy production and using it throughout the ship's stay to prevent the use of conventional fuels [4].

In general, the literature puts more emphasis on increasing the efficiency of ships and ports through more efficient equipment, route and port call planning, communication between ships and ports, and others. The articles on reducing emissions and greening ports by integrating renewable energy sources also generally focus on solutions that can be realized on the water surface, such as installing wind power plants, using wave energy or floating solar panels, and with less emphasis on increasing the efficiency of port buildings. Port buildings play an important role in the smooth running of port activities. Therefore, this paper focused on analysing solutions to increase energy efficiency in a building in the port of Constanta. A cargo warehouse was chosen as a case study. Increasing the efficiency by integrating renewable technologies in such a building will help to reduce the environmental impact and increase economic efficiency. The main aim of the paper is to provide a best practice model for increasing efficiency and reducing environmental impact, which can be replicated in other types of port buildings. The analysis and results included in this study could be of interest for port authorities aiming to increase sustainability and reduce environmental impacts. The subject is also of interest to port building owners who, by increasing the energy efficiency of their buildings, can help to support these initiatives and benefit economically.

This article is organized as follows. To begin with, the main ideas drawn from a research in the scientific literature on increasing port efficiency, the need, importance, measures and others are presented and the EDGE platform is briefly introduced. Next, the applied methodology and the results obtained from the assessment of the current building sustainability using the platform are presented. Based on this assessment, a series of measures to increase energy efficiency are proposed, taking into account the high solar potential of the area. The economic benefits and opportunities to invest in these measures, in particular in the integration of renewable energy sources are then highlighted. Finally, the main conclusions of this analysis are presented.

3. THEORETICAL BACKGROUND

3.1 Energy efficiency in port facilities

Satta Giovanni et al. found that energy efficiency improvement and renewable energy production are among the most implemented green strategies addressed by Italian Port Management Organizations. For increasing energy efficiency, replacing lighting fixtures, modernizing handling equipment and improving building efficiency are preferred, while for renewable energy production, the installation of photovoltaic plants is preferred due to their affordability, feasibility and possibility to be mounted on building roofs [5]. The implementation of green technologies such as solar panels offers substantial energy efficiency and carbon reduction benefits [6-7]. Also, the diversity of renewable energy generation installed on buildings can provide stability. The use of a PV system combined with a wind system assisted by a management system to power two buildings in the harbours reduces the uncertainty of output, and a storage system could cover periods when the output of both is low [8]. Due to their high energy consumption, ports have strong connections to the energy grid and are considered ideal for the installation of very large renewable energy generation capacities [9]. The very large production of green energy concentrated at a single point significantly increases the potential for the development of energy storage in the form of green hydrogen [10]. In such a port, the logistics system and the energy system are tightly coupled, which means that energy consumption in ports is influenced by the logistics operation [11]. Most port facilities have complex logistics, so collaborative energy-logistics optimization is required for port-integrated renewable energy systems to reach their full potential. This leads to improved economic and environmental efficiency of ports [12].

Warehouses are among the basic facilities needed for commodity management. Thus, due to the warehousing services they provide, they are a source of revenue for ports [13]. Because of this, increasing the sustainability of these buildings leads to cost reduction and thus maximizing revenues.

3.2 The EDGE platform

EDGE is an online platform available to people (owners, managers, constructors, engineers) interested in increasing the sustainability of a building. Based on input data, the platform estimates the building's energy efficiency, water consumption and the sustainability of the materials used. This estimation is obtained by a comparative analysis of the building with a reference model of the platform, built based on European and national energy performance standards and the building rules, regulations and practices applied in the country. The platform allows the analysis of several building types such as residential buildings, service buildings, warehouses or light industrial buildings. Finally, the platform performs calculations on energy consumption, heat transfer, renewable energy requirements and others based on the specific climatic conditions for the area where the building is located [14-16].

4. RESEARCH

This section presents the research methodology, the input data of the building entered the EDGE platform and the results of its sustainability assessment. Based on the results, the main areas of low efficiency are identified, and a method is proposed to increase energy efficiency by implementing measures that mainly aim at harnessing the solar potential of the area. Finally, a brief economic analysis of the economic benefits and opportunities of integrating the proposed method is made.

4.1 Research methodology

The research conducted in this article used a storage building located in the port of Constanta as a case study. The research methodology (Figure 1) consisted of carrying out simulations using the EDGE platform to study the impact of certain measures to increase energy efficiency.

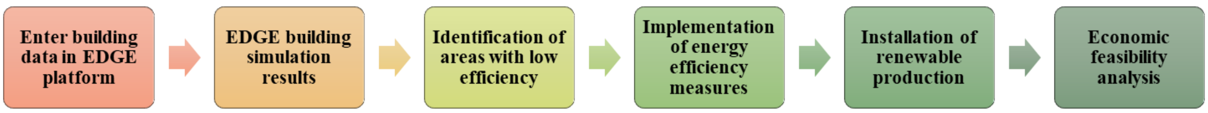

Figure 1. Research methodology

To carry out the simulation, it was necessary to introduce the constructive characteristics of the building (dimensions, location, orientation, compartmentalization, height), the performance of the equipment for heating, cooling, domestic hot water preparation, lighting, water flow from the sinks and the volume of the WC tanks and the type, thickness and conductivity of the materials used in the construction of the building. After assessing the efficiency of the building, the systems with low efficiency were identified and measures to increase their efficiency and reduce the energy consumption of the buildings by installing renewable energy systems using photovoltaic panels were analysed. Finally, the economic feasibility of the proposed methods was analysed.

Input data

For this article a warehouse building located in the port of Constanta in Romania was chosen as a case study. The building was constructed in 2010, has a total area of 11400 m^2, and consists of a main warehousing section and a secondary office section. The office section accounts for only 10.53% of the building's floor area and is spread over three floors. Structurally, the building is constructed of metal columns and reinforced concrete slabs. The exterior of the building is made of aluminium sandwich panels with 100 and 150 mm mineral wool insulation. The heat transfer coefficients for the roof, floor and exterior walls are 0.35, 0.32 and 0.35 W/ (m^2K). The glazed area of the building is small at 8.37 % with double glazing with a heat transfer coefficient of 1.1 W/ (m^2K). Cooling of the building is provided by a RADOX chiller with a cooling capacity of 147.4 kW and a coefficient of performance of 2.94 W/W. The heating of the building is provided by two Buderus natural gas condensing boilers with a capacity of 690 kW and an efficiency of 93%. Domestic hot water is produced locally using 10 electric boilers, one 80-liter and nine 10-liters, with an average efficiency of 37.5%. The consumption of hot water is mainly due to sinks in bathrooms and kitchens, about 4 l/min, and cold water from toilet basins. The indoor lighting is realized with fluorescent luminaires with efficiency close to that of the reference model in the EDGE platform. The outdoor lighting efficiency is 100 lm /W.

4.2 Research results

Thus, the building simulation obtained with the EDGE platform (Figure 2) shows that compared to the reference model, the storage building analysed is 26.54% more energy efficient, 50.17% more water efficient and uses 35% more sustainable materials. Also, according to the calculations made by the platform, the annual energy saving is 318.06 MWh/year and the amount of operational emissions is reduced by 295.88 tCO_2/year.

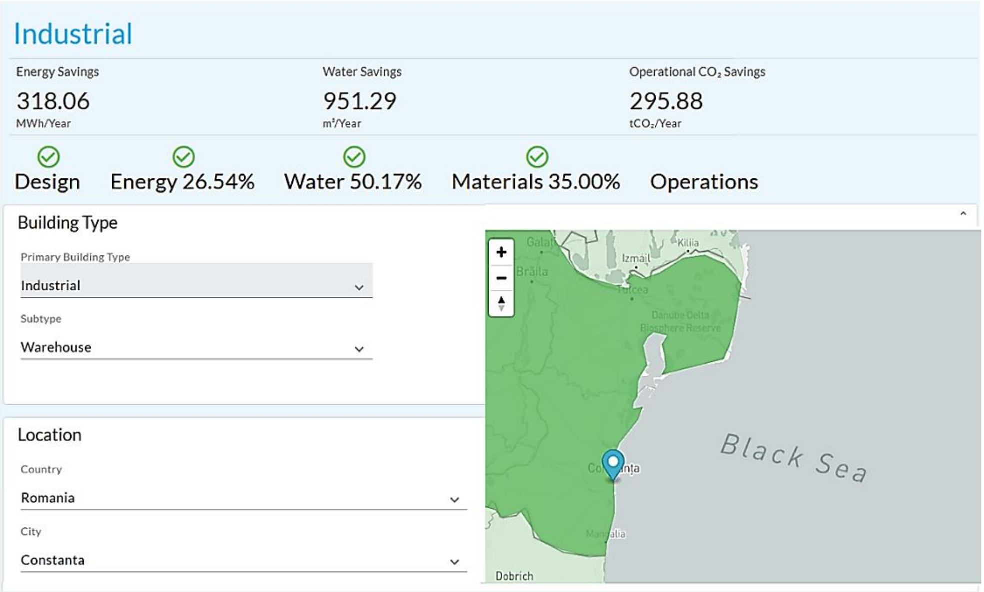

Figure 2. Print Screen of the warehouse simulation results using the EDGE platform

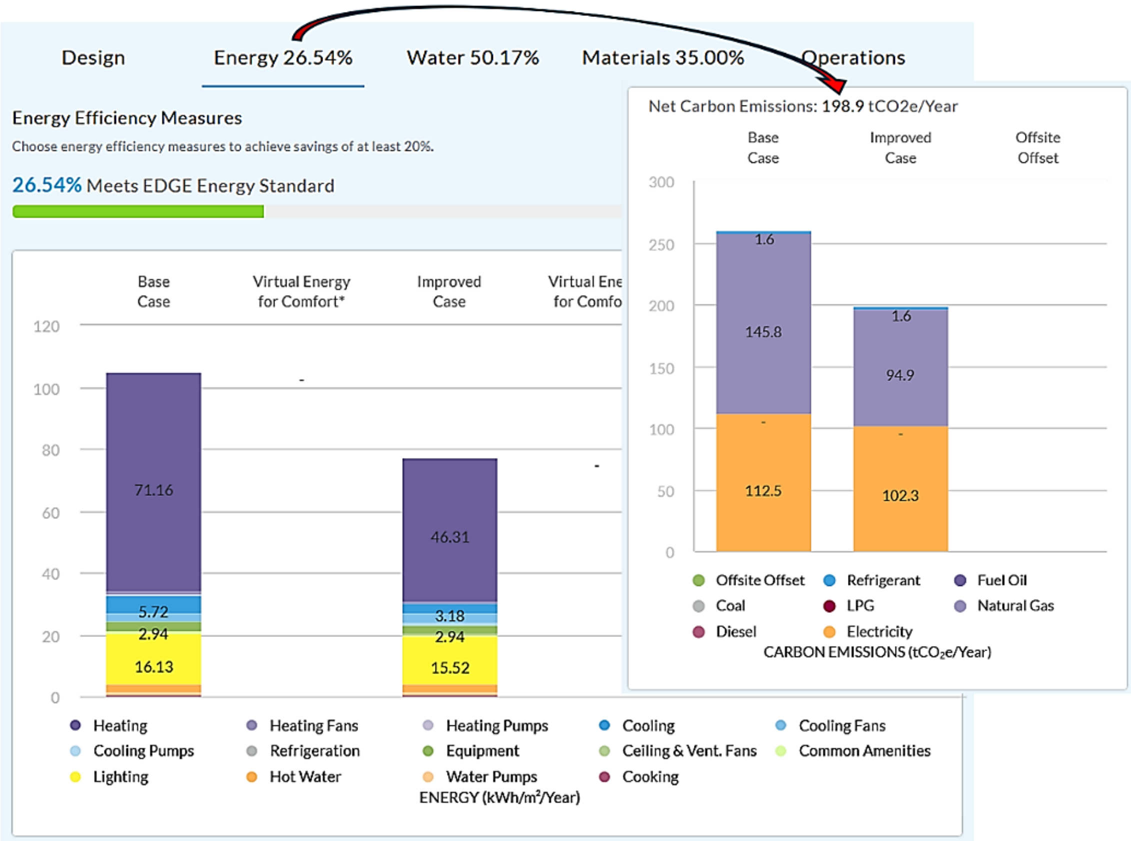

Figure 3. Print Screen of "Energy Efficiency" results

The higher building efficiency of more than 20% compared to the reference model is mainly due to the cooling and heating systems of the building, as can be seen in Figure 3. It can also be seen that the main areas with low efficiency are the indoor lighting system and the domestic hot water preparation system. Energy consumption and carbon emissions are closely linked in a cause-effect relationship, with energy production being one of the most important sources of global pollution due to the continued use of fossil fuels in production. Thus, according to the platform the analysed building has net emissions of 198.9 tCO_2e /year.

Water consumption is mainly from WC tanks and bathroom and kitchen sinks and is relatively low as can be seen in Figure 4. This is due to the low consumption of the bathroom and kitchen sinks of less than 4 l/min achieved by aerators mounted on taps.

The analysis of embodied carbon in materials shows a high efficiency of 35% due to the use of materials that have been extracted, manufactured and transported to the site with lower emissions, or from which lower quantities were used than in reference model of the platform. In Figure 5 it can be seen that for the materials used in the roof, exterior walls and floors, almost half less emissions were emitted than in the reference model.

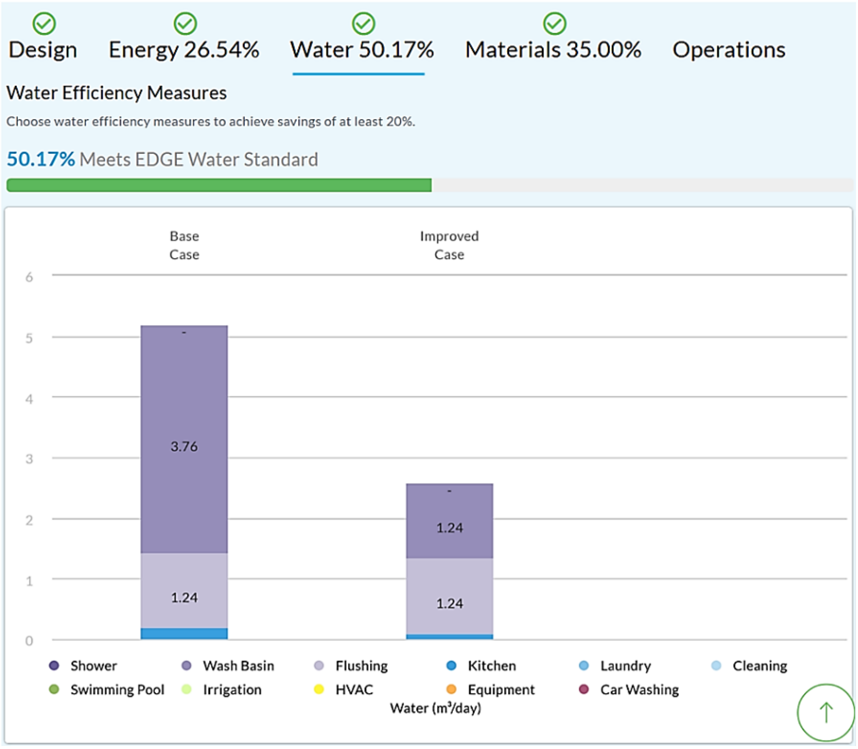

Figure 4. Print Screen of "Water Efficiency" results

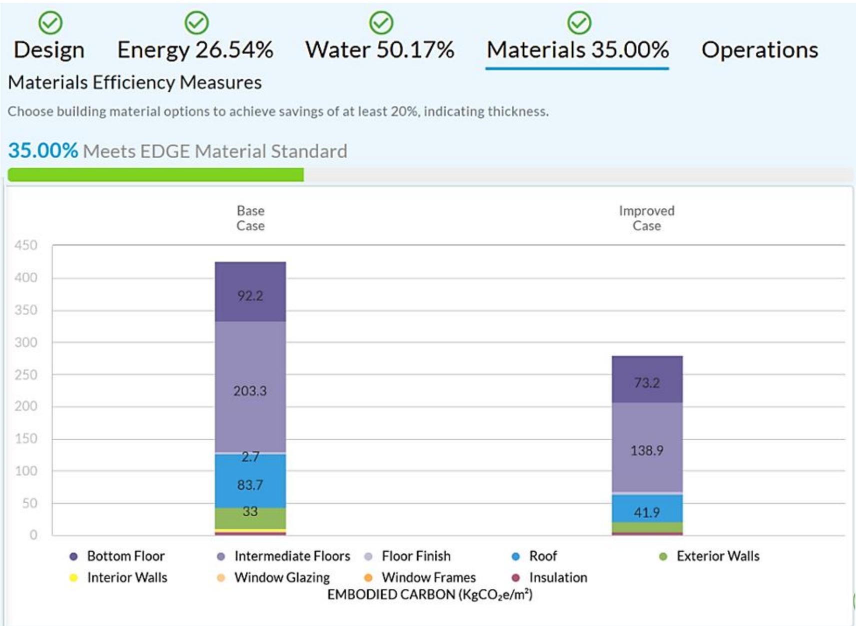

Figure 5. Print Screen of "Materials Efficiency" results

4.3 Solutions to increase energy efficiency by harnessing the solar potential of the area

Depending on the specifics of the port area and climate, several methods can be used for port buildings to increase energy efficiency, such as using wave energy, installing wind turbines, installing photovoltaic panels and others. According to available data, Romania has a solar potential for electricity production of 1.2 TWh in a year [17], with Dobrogea being the second-highest area with increased solar potential (Figure 6), after the Danube Delta [18-20]. Considering this particularity of the area, the article will focus on the valorisation of the high solar potential of the area in Dobrogea where the warehouse is located, namely the port of Constanța County.

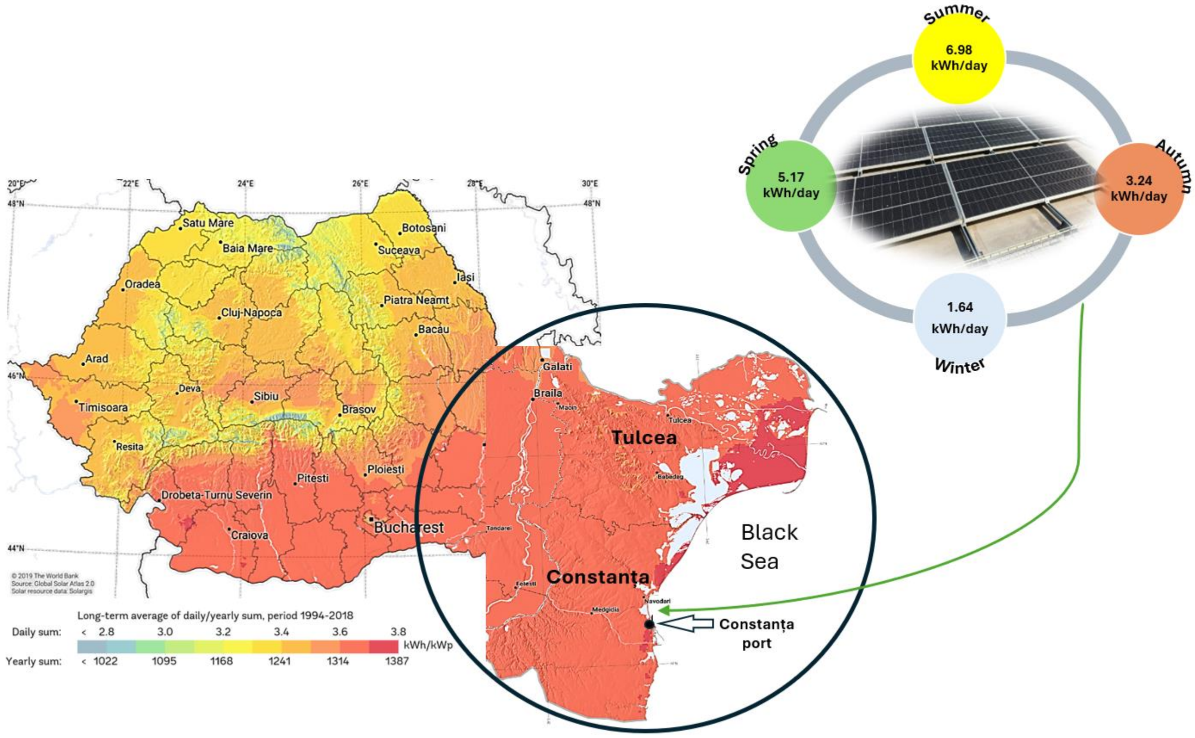

Figure 6. Photovoltaic potential of the port of Constanta in the Dobrogea region [21,22]

However, before analysing the benefits of installing a photovoltaic power plant, it is important to carry out rehabilitation, replacement or modernization works on the low efficiency areas of the building. Thus, the first step is to make the lighting system more efficient. This will be accomplished by replacing all fluorescent with LED fixtures with an average luminous efficacy of 124 lm /W. This measure will, according to the platform results, contribute to an energy efficiency increase from 26.54% to 31.00%. The cost of replacing the lighting system is shown in Table 1.

Table 1. Investment to increase the efficiency of the lighting system

Equipment	*Luminous efficacy [lm/W]*	*No.*	*Price [€/equip.]*	*Total price [€]*
KeyLine LED luminaire	132	186	157.04	29,209.44
CoreLine Panel	120	212	110.71	23,470.52
LED wall light	93.33	20	44.40	888

The efficiency of the domestic hot water system can also be increased. Thus, it is proposed to install a pressurized solar system, including two panels with 40 thermal tubes and a 200 litre bivalent boiler with two coils and an electrical resistance of 3000 W. In terms of system integration, although the building does not have an integrated domestic hot water system, the position of the bathrooms and the dining room, coffee room and kitchen require low building works to install such a system, as they are in the same area of the building. This modification increases energy efficiency by 2.19%. Table 2 shows the cost of replacing the domestic hot water system.

Table 2. Investment to increase the efficiency of the hot water system

Equipment	*Boiler capacity [l]*	*Power [W]*	*No.*	*Price [€/equip.]*	*Total price [€]*
Solar system	200	3000	1	1,429	1,429

The two measures lead to a building energy efficiency of 33.19% and a reduction of the building's annual operational emissions of 324.53 tCO_2. Thus, by making the building's main areas of consumption more efficient, it is now possible to size a photovoltaic power plant on the roof. According to the EDGE platform calculations, a PV capacity of 426.15 kWp needs to be installed.

If the project utilizes 470 Wp panels at 1800 x 1134 mm, a total of 907 photovoltaic panels would need to be installed in order to cover the total electricity consumption. The location of the port of Constanta is at a latitude of 44.479^o, the recommended tilt angle for the panels is 33.4^o [23], and the declination angle of the sun is 23.45^o [24]. The panels will be mounted facing south with a row spacing of approximately 1195 mm. In this situation, the panels will occupy an area of approximately 3808 m^2. The warehouse roof has an area of approximately 9796 m^2, of which approximately 800 m^2 are allocated to smoke traps and polycarbonate skylights. Thus, it is considered that the available area is sufficient for both the installation of the domestic hot water preparation system and the photovoltaic power plant. The installation of the photovoltaic power plant requires the installation and purchase of 3 inverters of 150 kW to connect the panels to the building's electrical system. It is also necessary to install a smart meter for the connection of the PV plant to the National Energy System in order to monitor the energy production and consumption of the grid, but this meter is provided by the operator of the distribution grid to which the PV system is connected. Table 3 shows the cost of PV plant.

Table 3. Invest to reduce building energy consumption

Equipment	*Power [kW]*	*No.*	*Price [€/equip.]*	*Total price [€]*
Photovoltaic panels	0.470	907	57.81	52,433.67
Inverters	150	3	7,044	21,132

Following the implementation of all the measures, the energy efficiency increases to 53.24%, the amount of energy saved per year increases to 638.4 MWh/year, and the reduction in operational emissions reaches 493.08 tCO_2/year), as shown in Figure 7. As the platform aims to reduce the carbon footprint, it scales the installed renewable energy capacity requirement to cover the entire energy consumption of the building each month. Thus, the entire electricity consumption is supported by the PV plant and is therefore considered to be zero, leaving only the natural gas consumption of the plants in the figure. The annual net emissions (tCO_2e/year) are also significantly reduced, leaving only the emissions from the cooling system. Figure 8 summarizes the results of each efficiency measure.

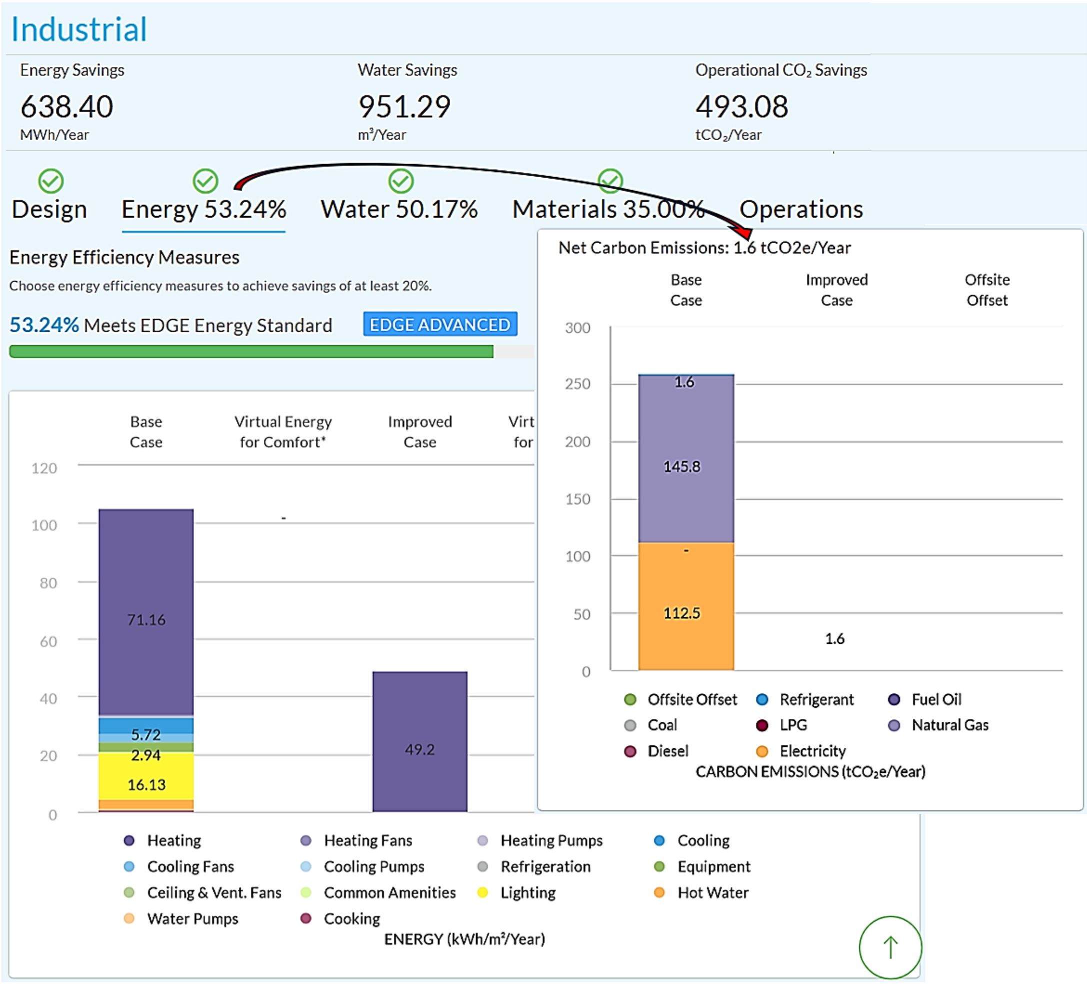

Figure 7. Print Screen of the results after replacing the lighting and hot water systems and installing the PV plant

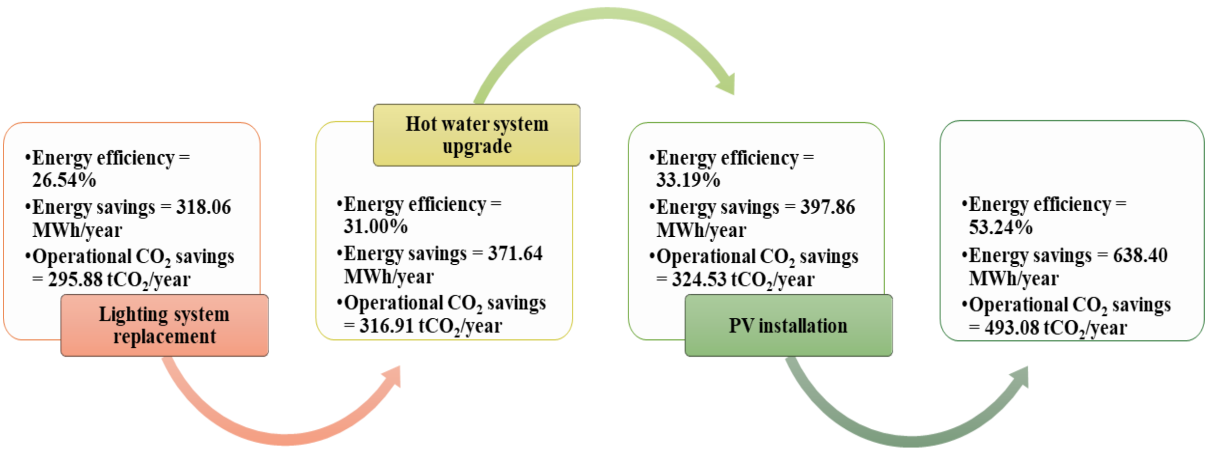

Figure 8. Summary of results for each energy efficiency improvement measure

4.4 Discussions and implications

The total cost for purchasing the equipment would reach €128,562.63. Calculations made by the EDGE platform show that the photovoltaic plant would have an energy production of 777,730 kWh /year in perfect conditions. However, a real-world scenario would see the photovoltaic panels produce approximately 512,195 kWh /year [25]. The energy consumption of the building is about 176,450 kWh /year, or 14,704.167 kWh /month. As shown Figure 9, there is only one winter month (December) in which the energy production is expected to be under the monthly estimated consumption. This will result in electricity purchase costs to cover the needs for the month of December. Following the implementation of the energy efficiency measures, in particular the installation of the photovoltaic plant, the energy consumption will be zero, which means that, at a fixed price of 1.3 RON/kWh, the annual savings would total about €46,105 (229,370.94 RON/year).

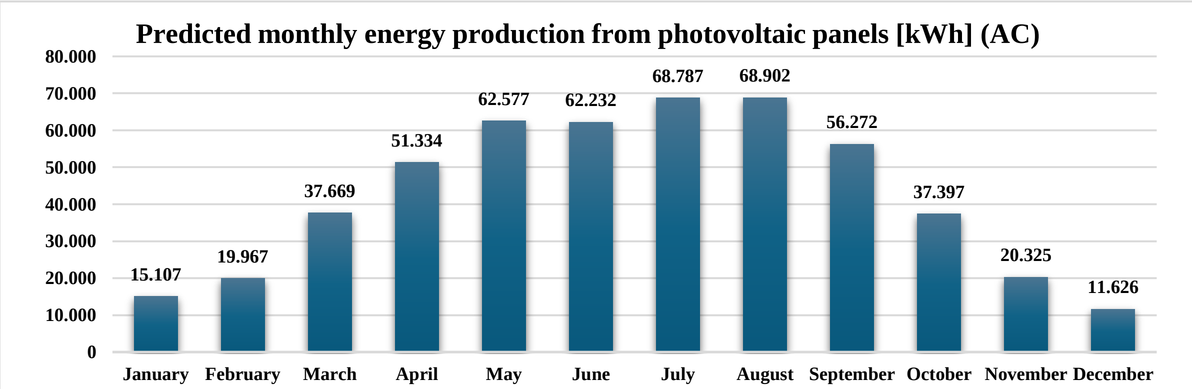

Figure 9. Predicted electricity production of the 426.29 kWp PV plant for each month of the year [25]

It is also noted that in the summer months, energy production is more than four times the approximate monthly consumption. Thus, the approximate amount of energy to be delivered to the national grid will be 335,745 kWh /year. According to the National Electricity Market Operator, the weighted average sales price in 2023 was 108.51 €/MWh [26]. If the same average price applies to 2025, the annual income from the production and sale of electricity would be approximately €36,431.69. Performing a simple calculation with the help of the IRR (Internal Rate of Return) function in Excel office application, it appears that in the 12 years of warranty of the photovoltaic panels assumed by the manufacturer, the investment for purchasing the necessary equipment to realize the energy efficiency increase is feasible (IRR = 26.68%). Even more, the cost of investment can be covered in less than five years just from the sale of the extra energy produced by the photovoltaic panels. It should be noted that this analysis does not take into account the costs of equipment transportation, the cost of laying the necessary pipes for domestic hot water, the purchase of other necessary equipment (cables), the costs of installation, maintenance and replacement of the equipment, the costs of purchasing electricity during periods when the system does not produce sufficient energy. Even with an increased investment of 50% (about €65,000), the project would be feasible (IRR = 15.47%) and would produce a profit in less than nine years according to the calculations.

Moreover, the purchase of a battery storage system is encouraged, which according to the calculations does not have to exceed the total cost (purchase, transportation, installation) of €50,000 for the investment to be feasible in the 12 years. The calculations have been made without taking into account discounts, or additional costs with taking out a loan to cover the investment. It is also worth mentioning that the expected lifespan of the photovoltaic panels is 30 years.

5. CONCLUSIONS

As a result of this study, the following conclusions were reached:
(1) This paper contributes at a theoretical level to the expansion of literature in the field of opportunities to increase energy efficiency by integrating renewable energy sources in port buildings.
(2) From a practical point of view, the presented method can be replicated for other types of port buildings and is a valuable guide that can be used by port authorities and port building owners to integrate renewable energy sources to reduce energy consumption, costs and emissions.
(3) The application of the energy efficiency improvement method studied in this article led to a doubling of the building's energy efficiency and annual energy savings. It also resulted in a reduction of operational emissions by 66.65%.
(4) In addition to reducing the electricity consumption bill and reducing emissions, the integration of the method presented in the article also leads to economic benefits, as the investment can be recovered in less than 9 years. The panels come with a 12-year warranty offered by the manufacturer and are expected to operate at maximum efficiency for 30 years. The income realized during the 12 years of the panels' warranty can be invested in the purchase of a storage system with costs up to €50,000.
(5) The research is relatively limited and has been narrowed down to a specific component of the port infrastructure, a storage building. Also, methods to increase energy efficiency have focused on harnessing the solar potential. The work can be extended to study the integration of several renewable energy sources such as wind energy, wave energy and others. The research can also be continued in the future by extending the study to other buildings/facilities of the port, aiming to study a global solution to transform the port of Constanța into a green port.

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