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Environmental and economic assessment of mariculture systems using a high share of renewable energy sources

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Abstract

Increased demand for fish products has resulted in greater investment in and modernization of the aquaculture sector. These processes have led to higher energy needs of aquaculture farms globally, resulting in their greater environmental impact. Fossil fuel is the main power source in aquaculture, and its combustion generates a large amount of Greenhouse Gases (GHGs) and other emissions. This paper considers the use of renewable energy sources (RESs) in mariculture systems to ensure at the same time cost-effective and environmentally friendly powering options. This paper investigates an alternative solution which relocates the majority of equipment and tasks from a mariculture vessel to a barge to reduce the energy demands of the vessel and to significantly lessen emissions of the system. The solution includes the full electrification of the workboat and the installation of PV cells and a wind turbine onboard the barge, combined with a diesel generator in an integrated power system. A Life-Cycle Assessment (LCA) was performed to evaluate the considered power system configurations from an environmental point of view, while a Life-Cycle Cost Assessment (LCCA) was performed to evaluate the economic performance of the proposed solutions. The results of the implementation of RESs in the mariculture system indicate an emission reduction of about 20% and an increase in capital costs by 0.61%. Feed reduction and the use of electricity in an alternative mariculture farm design in Croatia increase profitability by 4% in most cases.

Keywords: aquaculture, mariculture, carbon footprint, renewable energy sources, Life-Cycle Assessment, Life-Cycle Cost Assessment.

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NOMENCLATURE

Variables		Abbreviations	
A	area (m^2)	CF	Carbon Footprint
BC	battery capacity (kWh)	EU	European Union
BP	battery price (€)	FAO	Food and Agriculture Organization
BSE	battery's specific energy (kWh/kg)	GHG	Greenhouse Gas
BW	battery weight (kg)	GWP	Global Warming Potential
C	discounted annual cashflow (€)	IEA	International Energy Agency
D	diameter (m)	IMO	International Maritime Organization
d	day	LCA	Life-Cycle Assessment
DP	diesel price (€)	LCCA	Life-Cycle Cost Assessment
EC	energy consumption (kWh)	ME	Manufacturing emissions
EF	emission factor (g emission/kg fuel)	PTW	Pump-to-Wake
FC	fuel consumption (kg/h)	PV	Photovoltaic
i	time of cash flow (year)	RES	Renewable Energy Source
IC	investment cost (€)	WTP	Well-to-Pump
$LCFC$	Life-Cycle Fuel Cost (€)	WTW	Well-to-Wake
$LCMC$	Life-Cycle Maintenance Cost (€)		
n	lifetime (year)		
NPV	Net Present Value (€)		
P	power (kW)		
r	discount rate (%)		
SFC	specific fuel consumption (kg/kWh)		
TE	tailpipe emission (kg/h)		
t_s	daily sun hours (h)		
v	wind speed (m/s)		

Subscripts			
A	annual	η	efficiency (-)
B	battery-powered ship	ρ	density (kg/m^3)
D	diesel-powered ship		
rad	irradiation		
s	sun		
w	wind		

1 INTRODUCTION

Global demand for food is increasing as the human population grows, which leads to the sharp development of aquaculture. The development of this sector comes from fishing and the application of different types of fishing equipment for the cultivation of freshwater organisms (freshwater aquaculture) and marine organisms (mariculture). Over time, overfishing has occurred, which endangers the ecosystems. For this reason, aquaculture systems have been designed to grow organisms for food production, and spawning has been applied to rebuild fish stocks. According to the Food and Agriculture Organization (FAO) (2011), in 2008, world aquaculture production reached 52.5 million tonnes (excluding marine plants), with an annual increase of 8.4%. By 2018, world aquaculture production was 82.1 million tonnes, with an additional fishing catch of 96.4 million tonnes. The largest consumers and producers of fish and fish products are Asian countries, especially China. A sharp increase in production by 2018 was seen in North and South America, Africa and Oceania. Europe's fish production declined slightly from the 1980s on, but, in recent years, it has been recovering, primarily due to the development of mariculture in Norway (FAO, 2020). Aquaculture is a part of the Blue Growth sector, with large growth expected in the future (European MSP Platform, 2021). The European Commission encourages the production and competitiveness of aquaculture through reform of the Common Fisheries Policy and through employment in aquaculture, especially in coastal communities (European MSP Platform, 2021).

1.1 State of the art in fish farming

Aquaculture is a wide area that can be divided according to different criteria. The basic division is seawater and freshwater aquaculture, depending on the level of salinity of the habitat. Another example of differentiation is water-based, land-based, recirculating and integrated farming systems. Each technique requires a thorough decision-making process to design a quality farming system (FAO, 1987). Typical mariculture systems consist of cages, fishing vessels and an onshore energy network. In the majority of fishing vessels, energy is supplied by fossil fuels, which create a major environmental problem due to the harmful emissions generated by their combustion (Parker et al., 2015).

Sustainable farming methods are being investigated to reduce the environmental impact of mariculture farms, especially by electrifying the entire fleet. A good example of an environmentally friendly mariculture farm can be found in Norway. In 2015, Norway was the greatest aquaculture producer in Europe, exceeding the European Union (EU) in volume and value by 2% (Eurostat, 2020). In 2013, FAO (2020) ranked Norway as the world's largest producer of marine finfish, thanks to its salmon production. Norway has signed several agreements aimed at reducing its environmental footprint, with a strong focus on national sea transport and its fishing sector (Schau et al., 2009). According to Syse (2016), 50% of Norwegian fish farms still use diesel generators to produce electricity, while the rest are connected to the national electricity grid, whose major source is clean hydropower with a share of 95%. The goal is to electrify the entire sector. Considering the economic viability of the mariculture sector and the high share of Renewable Energy Sources (RESs) in the industry (Syse, 2016), similar steps should be taken in other countries.

Bohnes and Laurent (2020) conducted a detailed analysis of the environmental impact of mariculture production. The study included the impact of the infrastructure itself (materials, chemicals, nutrients, etc.), as well as the impact of feed decomposition and overall energy use. The infrastructural materials in prolonged contact with salt water can decompose and release harmful chemicals, especially the surface layers on which various antifouling coatings are most often found. However, fish feed and energy have the greatest environmental impact. Uncontrolled feeding creates an environmental problem by depositing uneaten feed on the seabed and impacting the growth of marine flora, while feed production and transportation itself result in Greenhouse Gas (GHGs) emissions, as well as other emissions. Automated feeders, monitoring systems, sensors and other equipment help control environmental conditions but increase the energy needs of the farms (Winther et al., 2020).

GHGs emissions refer to the emissions of carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and fluorinated gases, in low concentrations. These emissions cause the greenhouse effect, which results in the warming of the Earth's surface, causing climate change (UNFCCC, 2021). One of the latest climate agreements is the Paris Agreement (2016) which aims to keep the global temperature rise below 2°C above the pre-industrial level and limit the temperature increase to 1.5°C (UNFCCC, 2021). Considering that the high concentration of CO_2 in the atmosphere greatly contributes to global warming, following the United Nations stance, all industrial sectors should contribute to reducing their Carbon Footprint (CF), including the marine sector, even though it generates a small share of global CO_2 emissions compared to land transport (IMO, 2014). The term CF represents a measure of the total amount of CO_2 emissions that are directly and indirectly caused by an activity or are accumulated over the life stages of a product. The CF can be expressed in tonnes of CO_2 or tonnes of CO_2 equivalent (CO_2-eq) (Wiedmann and Minx, 2008).

Several research projects have already been undertaken on replacing fossil fuels as the main energy source in mariculture. Mok and Gaziulusoy (2018) investigated a salmon trout mariculture farm in Finland. They developed a strategic design framework focused on anticipating and mitigating foreseeable problems, such as industrial pollution. Another perspective is given by Ton Nu Hai et al. (2020), who stated that the environmental impact of a mariculture farm is influenced not only by the production process but also by the production environment. In their case study, they compared two lobster farms located in Vietnam and concluded that various parameters, from nutrient input to farm size and the distance between two farms, have a major impact on their environmental footprint. Especially high levels of CF can be found on a shrimp farm, due to the emissions of commercial and biological feed and the use of different substances for improving water quality (Chang et al., 2017). They emphasized the importance of integrating energy-conserving technology in aquaculture to reduce the CF. A common assessment tool used in the mentioned studies is the Life-Cycle Assessment (LCA), which is used to estimate emissions through a product's lifecycle (Chang et al., 2017). In general, the reduction of the CF in the context of an aquaculture farm can be achieved in various ways, including by integrating RESs into the system.

Statistical analysis performed by the International Energy Agency (IEA) shows an increase in the share of hydropower and wind power worldwide, while other forms of renewable energy are less common (IEA, 2020). When it comes to aquaculture systems, sea, solar and wind energy are most often considered (Syse, 2016).

Large funds are being invested in the development of new technologies related to solar energy. Photovoltaic (PV) technology presents an affordable energy source but the main problem is the lack of suitable space to instal it, which is not an issue in the case of mariculture farms (Pringle et al., 2017). PV system efficiency depends on the level of solar irradiation and, therefore, countries with a high level of sunlight are ideal for it to be implemented. Research conducted by Gagliano et al. (2019) confirmed this assumption by examining the effectiveness of PV technology in three countries with different levels of solar irradiation. The greatest drawback of a PV system is low efficiency due to the absorption of a high percentage of irradiation into the PV cells, allowing them to heat or reflect energy into the environment (Herez et al., 2020). While the lab efficiency reaches higher levels (24% and higher), the practical efficiency remains at lower values, approx. 11-17% (Peng et al., 2017). The heating creates an additional problem since increasing the temperature by one degree causes a decrease in efficiency by 0.40-0.65%. The energy obtained through the PV system could drive sensors and devices for monitoring and controlling the growing conditions (nutrients, temperature, pH, salinity, turbidity, etc.), oxygenation manipulation, and lighting.

The exploitation of wind energy has significantly increased in recent years, especially in Northern Europe. Although similar technology is used for onshore wind farms as for inland ones, costs are increased due to difficult environmental conditions. Hadžić et al. (2014) presented an overview of offshore wind turbine structures, intending to reduce production costs and develop new technologies. Offshore wind turbines yield more energy than onshore ones but also require higher maintenance costs. Another way is to instal turbines on a floating feed barge, which is needed for an offshore aquaculture farm. This method of integration enables easier access for maintenance and reduces costs (Syse, 2016). However, the load capacity of the barge and thus the possible requirements to reduce feed should be considered.

By 2007, the Mediterranean area had almost three times more countries that showed increasing aquaculture production (Ottolenghi, 2008). This growth entailed an increase in the number of vessels and equipment, and market competition forced investment in automated equipment which consequently caused an increase in the environmental impact of mariculture farms. Furthermore, the farms occupy a significant part of the sea near the coast and interfere with the maritime tourism of the country (European MSP Platform, 2021). This conflict is especially apparent in Mediterranean countries such as Spain, Italy, Croatia, etc., where high annual profits are made during the tourist season even though they have a growing aquaculture sector. Therefore, investing in the development of mariculture farms not only has an environmental impact, but also has a high economic one (European MSP Platform, 2021).

The capital cost includes fixed expenses such as property costs (purchase or lease), the building of an onshore facility and the installation of cages. Parameters that change depending on the level of automatization are the number of fishing vessels and staff costs.

The number of cages and their type depend on the type of fish being cultivated. The procurement of smolts, fingerling or other sizes of fish seed can be carried out in several ways. For instance, some aquaculture farms buy the fish seed from spawning companies, while others procure fry and fingerling by catching and then transferring them to cages. This has a high impact on the final market price of the product since spawning also requires the investment of resources and energy consumption (Azazy et al., 2012).

Fish feed is a parameter of significant economic and environmental importance. Depending on the type of cultivated fish, a certain amount of feed is needed to breed a high-quality product and depends on the model of feeding (Luna et al., 2019). Conventional aquaculture farms, especially smaller ones, do not invest in the modernization of the feeding system, and the process is usually performed manually. Such a method fails to control the amount of feed given, which is why more than necessary is consumed, thus creating unnecessary expense. By introducing new technologies, the cost of fish feed and other particulars may be reduced, but other costs increase, as presented in Figure 1.

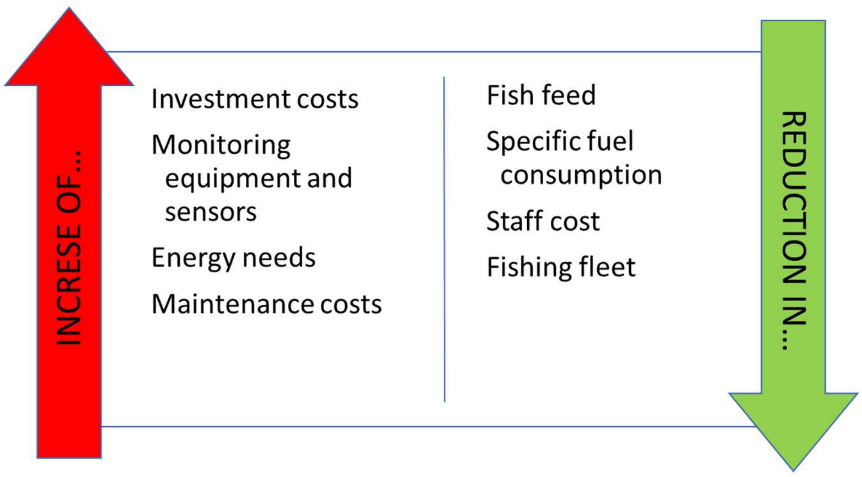

Figure 1. The impact of mariculture modernization on total costs

1.2 Research gap, aim and contribution of the paper

After an extensive literature review (over 200 publications), Badiola et al. (2018) emphasized the significance of determining the environmental impact of mariculture production and the need for improvement. As they stated, previous works dealing with sustainable production often did not include energy use and the economic and environmental impacts of production, especially in the mariculture sector. The replacement of fossil fuels by RESs is currently a trending topic in other industries (e.g. land transport), but research on their integration in mariculture is underrepresented. This paper seeks to find suitable solutions to the above problems using the example of a water-based mariculture farming system. Recently, Le Féon et al. (2021) presented a multi-attribute model called DEXiAqua for the assessment of sustainability of aquaculture systems via several indicators from technical domains and reference methods, among which life-cycle emissions and life-cycle costs play an important role. The model was applied to a case study of salmon Farming in France. However, Le Féon et al. (2021) indicate that more studies related to other systems with different technical properties and put in different context are desirable for future refinements of the model. Assessment of environmental impact of aquaculture projects in Chile between 1994 and 2019 presented by Rodríguez-Luna et al. (2021) belongs to this category of studies, where opportunities to improve environmental indicators of aquaculture systems are indicated.

Based on the above literature review, the following research gaps have been identified:

- There is a need for an accurate mathematical model to determine the environmental impact of mariculture farms;

- The integration of a higher share of renewables in the mariculture sector is desirable, but there is no clear insight into the viability of this process for randomly selected fish farms;
- References dealing with the fish farming sector regularly underestimate the problem of energy supply, and, to the best of the authors' knowledge, there is no reference simultaneously considering the life-cycle emissions and life-cycle costs of a fish farm and the corresponding workboats for its operation,
- Even though the Croatian mariculture sector is growing, to the best of the authors' knowledge there are no relevant studies examining its environmental impact and the appropriate measures to reduce it in a cost-effective way.

According to the Ministry of Agriculture (2020), while Croatian aquaculture takes 8th place in terms of quantity, in terms of value of production it is in 13th place in the EU. Croatia has the potential to develop a viable mariculture sector, but further investment is needed to ensure higher revenue and greater competitiveness (Eurofish, 2021). The process of optimization is already in progress (Kljaković, 2017 and Šteko, 2019), but mainly to ensure higher profits and less to improve environmental friendliness. Currently, there is an emphasis on increasing farm capacity and reducing fish feed.

This paper aims to tackle all the mentioned research gaps, by considering a mariculture farm powered by electricity generated by a higher share of renewables compared to conventional fossil-fuel powered configurations. The goal is to create an economically and environmentally sustainable solution with a higher share of RESs compared to existing ones and which can be applied to any aquaculture system, thus contributing directly to sustainability and cleaner production. The emission and costs of conventional mariculture systems and the proposed alternatives are evaluated by a Life-Cycle Assessment (LCA) and

Life-Cycle Cost Assessment (LCCA), respectively. Besides a lower environmental impact and financial savings over its lifetime, the alternative configuration allows for relocating the mariculture farm farther from the coast.

The original contribution of this paper includes:

- A model for the assessment of lifetime emissions and lifetime costs of mariculture systems;
- An insight into the viability of reducing the environmental impact of these systems through the integration of RESs;
- An alternative design of a mariculture system to reduce the environmental impact and the total costs of fish farming in Croatia.

The study deals with a mariculture system in Croatia with a high share of RESs, where different types of RESs are analysed and the most important issues inherent in these technologies are discussed. The methodology is applicable more generally if a set of input data relevant for some other location is known.

2 METHODOLOGY

The basic design of a mariculture system consists of cages and working/fishing vessels with various equipment, Figure 2. To make the farm operable, vessels and onshore facilities that consume a certain amount of energy, and thus release GHG emissions, are required. The vessels are used for fish feeding, cage maintenance, harvesting fish, and cooling and storing it.

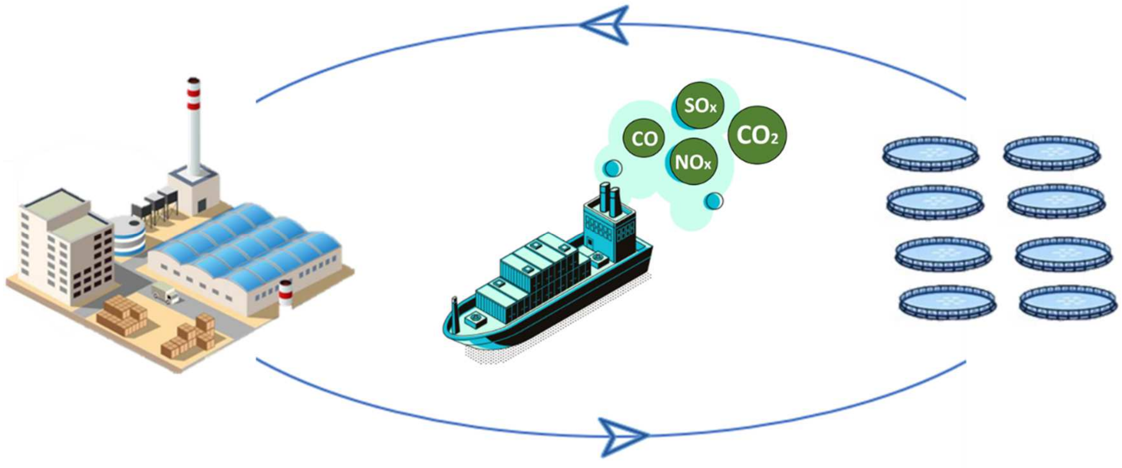

Figure 2. Model of a conventional mariculture system

By modernizing the farms, i.e. installing automated feeders and monitoring systems, the need for vessels declines as equipment is relocated onto a mariculture barge, Figure 3. The idea is to fully electrify the workboats and power the barge by using solar and wind energy, integrated with diesel generators.

Figure 3. Model of an electrified mariculture system

Since many power system configurations can meet the required energy needs, an analysis of several options is performed. The suitability of a power system configuration is determined not only by its lifetime economic performance but also by its environmental acceptability.

2.1 LCA

An LCA investigates the environmental impact of a system. In this paper, by using the LCA software GREET (2020), a comparative analysis is conducted with the focus on the CO_2-eq emissions released throughout life cycle of the system. The focus is on the emissions related to the power system, where they are analysed in the following phases:

I. The Well-to-Pump (WTP) phase – an analysis of a fuel cycle (from the extraction of raw materials to the production of fuel and its transportation to the refuelling station);
II. The Pump-to-Wake (PTW) phase – an analysis of fuel usage in a power system which causes tailpipe emissions;
III. The Manufacturing (ME) phase – an analysis of the manufacturing process of the main elements of a power system and their related released emissions.

In order to determine which power system is the most suitable, the following configurations are considered: (1) a diesel-powered system; (2) a battery-powered system; (3) a combination of wind and solar-powered system.

The first step in the LCA is to calculate the daily energy consumption, EC_{daily} (kWh), of the workboat. The value is calculated by dividing the daily fuel consumption, FC_{daily} (kg), with the specific fuel consumption, SFC (kg/kWh), which depends on the type of power system used.

Diesel-powered systems include processes from diesel-engine manufacturing to diesel combustion in the engine. The process can be divided into phases, as presented in Figure 4. The Well-to-Wake (WTW) phase relates to emissions released from the processes in the WTP phase and the process of product use, i.e. the PTW phase. The WTP phase refers to the production and distribution of diesel. The processes of raw material recovery, refining and distribution are described by using the parameters for diesel. To give a true representation of the environmental impact of a diesel system, the manufacturing process of a diesel engine is determined by the weight of the engine materials (Jeong et al., 2018). PTW emissions, also referred to as tailpipe emissions, *TE* (kg/h), are released due to the combustion of diesel in the engines and are calculated by the following Eq. (1) (IPCC, 2006):

$$TE = FC \cdot EF, \tag{1}$$

where *FC* represents the fuel consumption in kg/h and *EF* denotes the emission factor in kg gas/kg fuel. The GHG emissions factors for diesel are obtained from (IMO, 2014). For this calculation, the *SFC* of a diesel-powered vessel is assumed to be 0.215 kg/kWh (Perčić et al., 2020a). GHGs released during the combustion of diesel can be quantified as presented in the following Eq. (2) (Perčić et al., 2020b):

$$CF = GWP_{CO2} \cdot TE_{CO2} + GWP_{CH4} \cdot TE_{CH4} + GWP_{N2O} \cdot TE_{N20}, \tag{2}$$

where *GWP* ($CO_{2\text{-eq}}$) denotes the Global Warming Potential, a measure of how much energy the emission of one tonne of gas will absorb over a given period, relative to the emission of one tonne of CO_2 (Perčić et al., 2020b). This equation is used for the quantification of GHGs released also from the WTP and ME phases. The *GWP* data for CO_2, CH_4 and N_2O are obtained from (EPA, 2021).

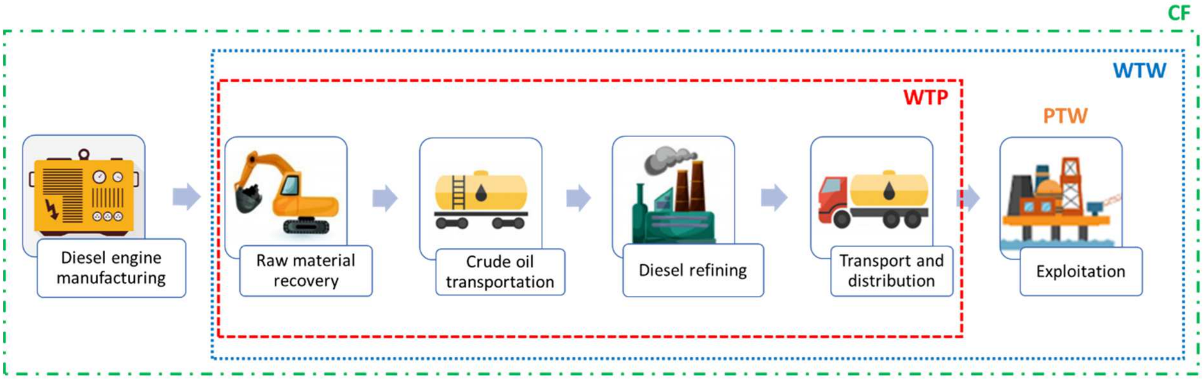

Figure 4. Processes included in the LCA of a diesel-power system

A battery-powered system configuration is investigated as an option for the electrification of a workboat in a mariculture farm. As concluded by Perčić et al. (2020b), a fully electrified vessel powered by a battery results in a major reduction of emissions. There are many types of batteries, but a Lithium-ion (Li-ion) battery is selected since it is the most suitable for maritime purposes Perčić et al. (2020b). The battery capacity, BC (kWh), sufficient to meet the required energy needs, is calculated as follows, Eq. (3):

$$BC = 1.5 \cdot EC_{daily}. \quad (3)$$

When the battery degradation and safety requirements are calculated in, the required capacities are increased by 50%.

The LCA of a battery-powered system configuration includes the manufacturing processes of an electric engine and the battery and the electricity generation process, presented in Figure 5. The energy density of a Li-ion battery with nickel manganese cobalt oxide (NMC) is 0.15-0.22 kWh/kg (Perčić et al., 2020b). To analyse the environmental impact of the battery, the weight of the battery, BW (kg), is calculated as in Eq. (4):

$$BW = \frac{BC}{BSE}, \quad (4)$$

where *BSE* presents the battery's specific energy, which equals 0.25 kWh/kg.

Another significant input is the replacement of the battery, which is assumed to be every 10 years. The environmental footprint of an electric engine is assumed to be equal to the environmental footprint of a diesel engine. The electricity generation process is affected by the national electricity mix of the country for which it is being investigated.

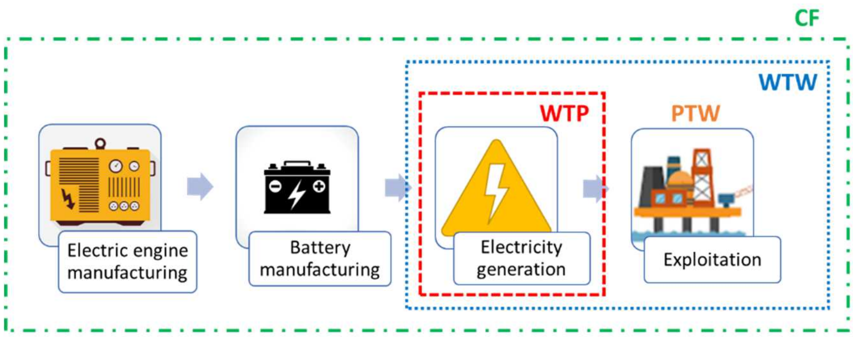

Figure 5. Processes included in the LCA of a battery-powered system

For the mariculture barge, the integration of RESs is considered, so that a part of the energy will be supplied by RESs and part by diesel generator. The higher the share of RESs, the lower the emissions are expected to be. Figure 6 presents the processes in the LCA of a combined wind and PV-cells-powered system.

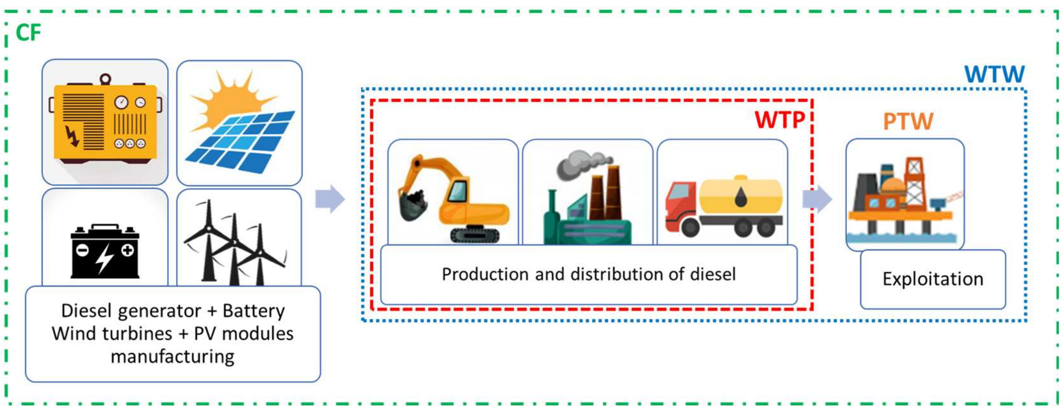

Figure 6. Processes included in the LCA of a wind-PV cells powered system

The PV-cells-power system configuration significantly depends on the weather conditions and the available installation area. Ančić et al. (2020) calculated the total annual energy production, E_{PV} (MJ), according to the following Eq. (5):

$$E_{PV} = \eta_{PV} \cdot E_{rad} \cdot A, \tag{5}$$

where η_{PV} represents the efficiency of the PV system, E_{rad} (MJ/m^2) denotes the average solar irradiance, and A (m^2) denotes the area covered by the PV cells. By dividing the calculated E_{PV} with the number of daily sun hours t_s (h), the power output of a PV system P_{PV} (kWh) is determined.

One of the processes includes manufacturing the PV modules, i.e. the weight of the materials from which these elements are constituted (Perčić et al., 2020a). The manufacturing process parameters are obtained from the GREET 2020 database.

The wind-power system configuration depends on the wind power density and the swept area of the turbine (Ghenai, 2012). The location of installation and the main particulars of the wind turbines have a significant role in determining the average wind potential. The wind power can be calculated according to Eq. (6):

$$P_W = \frac{1}{2} \cdot \rho \cdot A_w \cdot v^3, \tag{6}$$

where ρ (kg/m^3) denotes the air density, A_w (m^2) denotes the swept area, i.e. the area of a wind turbine, and v denotes (m/s) the wind speed. The area of a wind turbine can also be calculated as in Eq. (7):

$$A_w = \frac{D^2 \cdot \pi}{4}, \tag{7}$$

where D (m) denotes the diameter of a wind turbine.

The manufacturing process of wind turbines includes the weight of the materials from which they are constituted (Wang et al., 2017).

The system includes a diesel generator and a battery for energy storage. The battery capacity is calculated as 50% of daily energy needs since the RES system produces a small amount of energy that needs to be stored.

2.2 LCCA

An LCCA includes the total life-cycle costs of a system, e.g. the investment cost, the cost of fuel, maintenance costs, and other costs. Due to the expected introduction of carbon allowance in the future, i.e. the cost of a permit to emit CO_2, it is useful to calculate the cost-effectiveness of a different power system (Perčić et al., 2020b). The total costs of a mariculture system design are presented in Figure 7. The investment cost includes the capital costs of mariculture cages and the establishment of onshore facilities. The costs also include the price of fingerlings or smolts and staff wages. Exploitation costs include the costs of fuel consumed in the power system (transportation, distribution, fish handling), staff wages and the equipment needed for fish handling, and the cost of fish feed. Maintenance costs include different repairs, equipment replacement costs, veterinarians, maintenance staff, and similar. The last group covers the costs of farm automatization. These costs include the price of the installation of renewables, batteries and their replacement, and automated equipment.

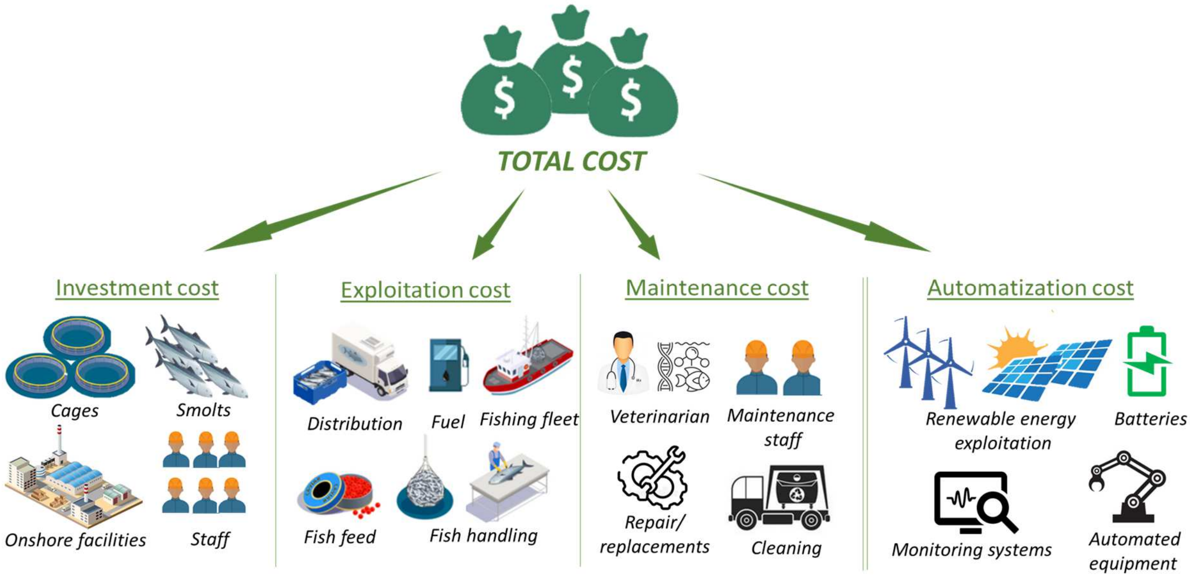

Figure 7. Total costs of a mariculture farming system

The LCCA of a diesel-powered system configuration contains information on the costs of a new diesel engine and its installation. The cost of a new diesel engine is calculated by multiplying the average power of the ship with the unit price of €250/kW (Perčić et al., 2020b). The life-cycle fuel cost ($LCFC_D$) is calculated according to Eq. (8):

$$LCFC_D = FC \cdot DP, \tag{8}$$

where FC denotes the lifetime fuel consumption in kg and DP denotes diesel fuel price in €/kg. The maintenance cost is assumed to be €0.014/kWh (Perčić et al., 2020b), and by multiplying it with the energy consumption of the ship the life-cycle maintenance cost is calculated ($LCMC_D$).

The capital cost has the greatest impact on the LCCA of a battery-powered system configuration. According to Perčić et al. (2020b), 45% of investment costs are the battery price, and the rest represents installation, the electric engine and additional equipment costs.

The battery price is assumed to be €200/kWh, Perčić et al. (2020b). The investment cost of a power system for a battery-powered vessel can be calculated as in Eq. (9):

$$IC_B = \frac{BC \cdot BP}{0.45}, \tag{9}$$

where BC denotes the battery capacity calculated according to eq. (3) and BP denotes the battery price. The $LCFC_B$ is determined by the energy consumption of a battery-powered vessel and the electricity cost (€/kWh), while the $LCMC_B$ depends on the battery capacity and the battery price anticipated after 10 years, which is assumed to be €169/kWh, Perčić et al. (2020b).

The LCCA of a wind-PV-cells-powered system configuration includes the investment costs of the PV system, which is calculated by multiplying the investment cost of PV cells (€/kW) with the total power of the PV system (kW), and the cost of a wind turbine. The investment cost of the wind turbine is assumed to be €3,000/kW (Hadžić et al., 2014) and of the PV system €1,116/kW (Perčić et al., 2020c). The maintenance cost of a PV system is assumed to be 20% of its investment cost, whereas the maintenance cost of a wind turbine is assumed to be 10% of the investment cost. Since the power system includes a diesel generator and a battery for energy storage, the investment and maintenance costs of each are also included in the LCCA.

2.3 Assessment of project profitability

To gain a complete insight into the system of RESs and its possible modifications, a technical and economic analysis of the system was conducted. By changing the technical characteristics of the system, such as wind speed, number of sunny hours, but also economic features such as the price of electricity, the net present value (*NPV*) changes. The *NPV* is calculated by the following Eq. (10) (Di Trapani et al., 2014):

$$NPV = \sum_{i=0}^{n} \frac{C_t}{(1+r)^i}, \quad (10)$$

where C_t denotes the discounted annual cashflows, i denotes the time of the cash flow, n represents the lifetime of the investment, and r denotes the discount rate.

The *NPV* is the main economic indicator for assessing the suitability of an investment programme. The greater the value, the sounder the investment is. If the *NPV* has a negative value, the investment programme is unacceptable. If the *NPV* is zero, it means that the income is enough to cover the costs of production, but there is no added profit.

3 CASE STUDY

Croatian mariculture consists mainly of the cultivation of finfish (fennel and seabass) and tuna. In this paper, a tuna farm near Zadar is investigated (Šteko, 2019). The Zadar region is known for the largest number of farms for white fish and tuna fish (Eurofish, 2020). With the growth of the Croatian mariculture sector, energy needs are increasing and thus the problem arises of environmental acceptability. The greatest environmental problem is created by the obsolete fishing fleet. One way to deal with this is to use RESs and to ensure the electrification of the mariculture systems, including the vessels.

The investigated location, presented in Figure 8, shows favourable energy characteristics for the use of RESs. Zadar is known for a large number of sunny hours t_s (h) throughout the year, and the horizontal irradiation is determined at 5,471 MJ/m^{2}year (Global Solar Atlas, 2021). The wind velocity is the highest during the night, while during the day it may achieve minimal values, especially during the summer. Farkas et al. (2019) indicated the “Jugo” and “Bora” as the most significant winds that can affect the annual amount of energy produced in Croatia. The mountainous area in the Croatian Littoral also has a great influence: it accelerates the winds which slow down as they approach the coast. For the purpose of this paper, the average velocity of 6.5 m/s is used in the calculation according to Hadžić et al. (2014). The wind density at an ambient temperature of 20°C is 1.2 kg/m^3.

Figure 8. The location of the investigated tuna farm, Zadar, Croatia

The investigated mariculture system consists of 22 cages with a diameter of 50 metres. The cage cost is set according to Rubino (2008), who determined a value of $30 per m^3 (approx. €25/m^3). The volume of the investigated farm is around 25,000 m^3 per cage. Therefore, the price is assumed to be €625,000 per cage. Maintenance of the cages is performed twice a year, using a net cleaner whose rental cost is estimated at around €25,000, including fuel consumption (Osterbo Gruppa, 2021). The staff is estimated to amount to six persons per cage, according to FAO (2020). The average monthly gross earning in Croatia is approx. €1,100 (Croatian Bureau of Statistics, 2021), which is adopted as the monthly payment cost per person in this paper. Veterinarians are also a necessary part of the staff and their monthly payment is estimated at €1,700/month.

The main particulars of a conventional mariculture vessel are presented in Table 1 (Atlantic Shipping Shipbrokers, 2021). The Croatian shipping sector uses “Eurodiesel Blue” as a fuel which is diesel with up to 0.5% sulphur. The raw material for diesel production in Croatia is crude oil, which is primarily transported from the Middle East and transported by tank trucks from the exploitation site to the port (500 km). From the port, the crude oil is loaded onto a tanker and shipped to Omišalj, Croatia (4,000 km), from where it is transported by pipeline to the Rijeka refinery (7 km). The fuel cost depends on the diesel cost and, in Croatia, its average price is €0.78/kg (Perčić et al., 2020b). In conventional mariculture farms, a reefer or wellboat type of vessel is needed for cooling and storage. Consequently, the energy consumption of vessels is higher, but this eliminates the feeding barge. According to available data (Basurko et al. (2016), Parker et al. (2014), FAO (2020)), the estimated fuel consumption of this type of vessel is 400 kg/t of the carried weight (fish, feed, ice etc.).

The investment cost of establishing a fish farm can be quite high (Šteko, 2019). Firstly, 30,000 fingerlings are procured. According to the data available on Eurofish (2021), procurement is usually performed by catching specimens (8-10 kg per fish) which requires a weekly cost of vessels and staff (estimated at €400). It is assumed that spawn procurement is performed twice a year, with an average duration of four weeks. According to FAO (2020), fish feed accounts for almost 50% of the total production cost. The cultivation of tuna requires 17 kg of feed per kg of fish a day. The fish are fed for 20-25 days monthly. By multiplying the required quantity with the number of specimens in a farm and the average fish weight, the amount of feed needed in a month can be calculated. After a market analysis, the cost is assumed to be €1.05/kg of feed. The cost per kg is assumed to be relatively low because, to the best of the authors' knowledge, the Croatian market is saturated with small finfish which is why it achieves a low wholesale price. The price of full-grown specimens (around 40 kg) is estimated at €30/kg (Sea Food Source, 2020). The annual overall production is approx. 1,300 tonnes of tuna.

By introducing RESs into mariculture farms, the conventional vessel can be replaced by a mariculture barge and workboat. The equipment from the conventional vessel, such as cooling and feeding systems, storage, kitchen appliances etc., can be relocated on the barge. Therefore, the vessel is needed only for transportation which reduces its energy needs and enables it to be powered by batteries. The energy characteristics of the farm after electrification are presented in Table 1.

Table 1. Comparison of the main particulars of a conventional and alternative mariculture system

	Conventional mariculture system	**Alternative mariculture system**	
		Workboat	**Feeding barge**
EC_{daily}, kWh	1,162.79	1,302.33	420
Power system	Diesel engine	Battery	RESs + diesel generator
FC, kg/d	250	0	41.28

In this paper, the workboat has a battery-powered-system configuration. The battery is charged from the national grid, assuming the electricity mix presented in Figure 9, which is directly available in the GREET 2020 database. According to Eurostat (2020), the average electricity price for non-household consumers is €0.13/kWh.

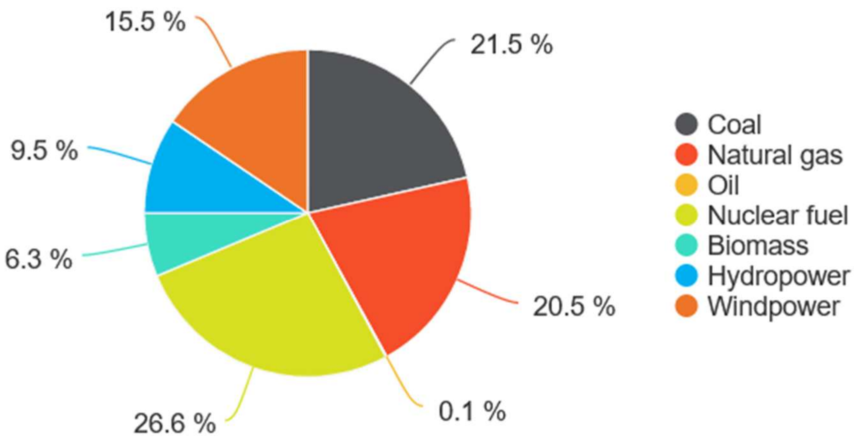

Figure 9. European electricity mix, GREET (2020)

Both the wind turbine and PV cells are placed on the barge. A 10-kW-powered turbine is chosen (Bergey Windpower, 2021). The PV cells cover most of the free surface of the barge, leaving space for the installation of the turbine. After calculating the power outputs of each system, it is concluded that it will not be possible to power the barge completely from RESs. Therefore, a diesel generator is installed, and a battery is added to store energy. The technical characteristics of the RES systems are presented in Table 2.

Table 2. Technical characteristics of RES systems

Wind Turbine		PV system	
Rated capacity (kW)	10	A (m^2)	700
D (m)	7	η (%)	17
Swept area (m^2)	38.47	t_s (h)	7
Total mass (kg)	475	E_{rad} (MJ/m^2) per day	5,824
Power output - daily (kWh)	152.65	Power output - daily (kWh)	75.35
Total power output = 228 kWh/d			

4 RESULTS

The results of the LCA and LCCA, performed for a conventional and an alternative mariculture farm design, are presented in Figures 10 and 11. The LCA of a conventional mariculture farm shows a high CF. When compared to the LCA results of an alternative mariculture farm, a CF reduction of 19.62% is achieved by electrification. The majority of emissions in the alternative design is related to electricity production and the calculated amounts are directly dependent on the electricity mix used, i.e. by raising the share of RES in the electricity mix, a positive impact on emission reduction would be achieved. In the alternative mariculture system, 21.9% of the total CF is generated by the barge, while the remaining 78.1% is generated by the workboat, Figure 10 – right-hand graph.

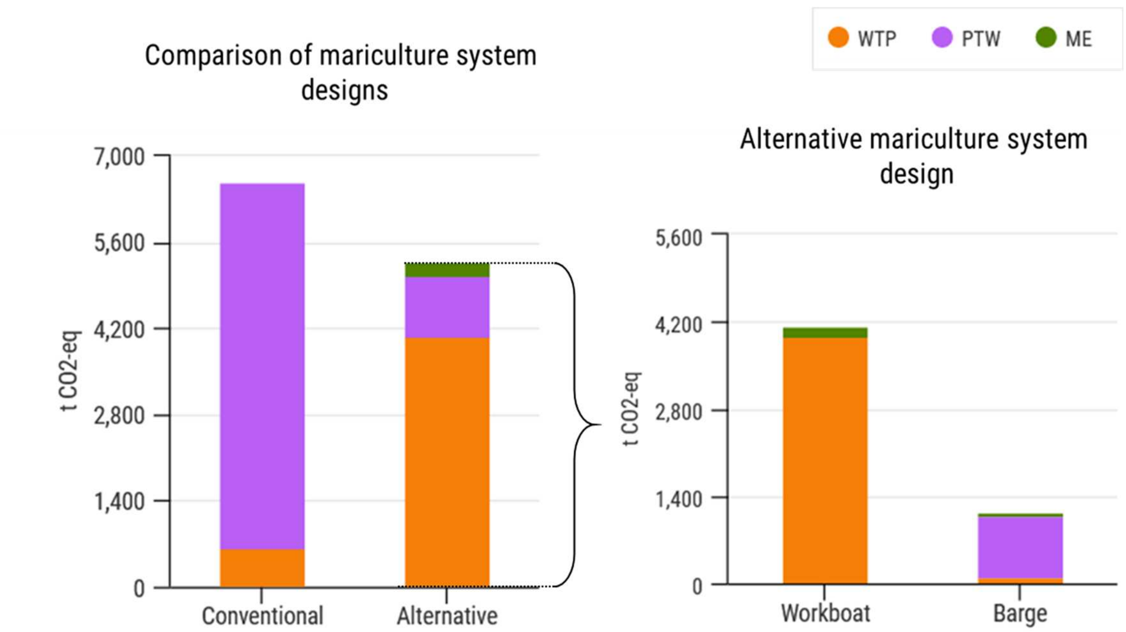

Figure 10. The LCA results

The LCCA results indicate that the costs of the alternative design are 3.23% lower than those of the conventional one. The alternative design entails slightly higher capital, maintenance and energy costs, but the operating costs are 42.80%. lower, which is a significant reduction.

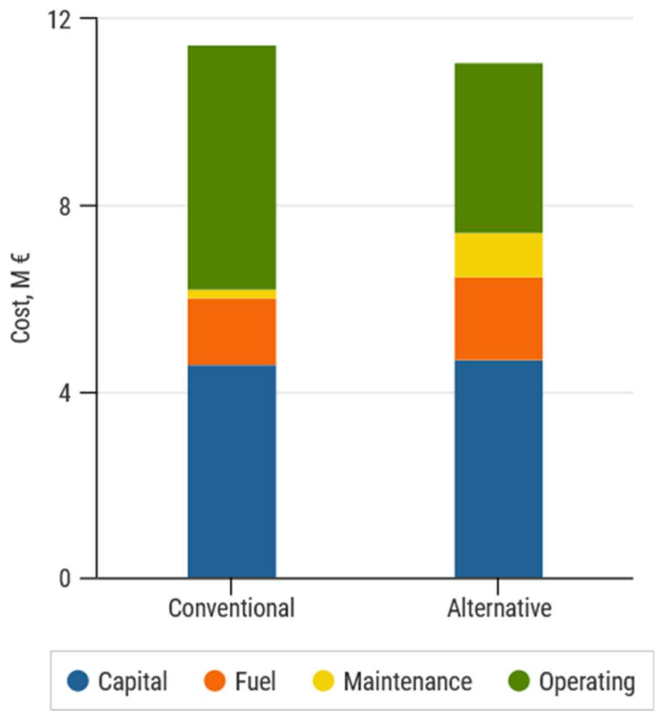

Figure 11. The LCCA results

The economic analysis shows that conventional farms require slightly less investment than alternative designs, Table 3. The greatest impact is seen in the operating costs where a reduction in the number of employees, and thus a reduction in staff costs, is calculated.

Table 3. Financial plan of a mariculture farm (after 1 year)

	CONVENTIONAL	ALTERNATIVE
Capital cost (M €)	17.91	18.02
Fuel cost (M €)	1.43	1.64
Operating cost (M €)	5.23	3.66
Maintenance cost (M €)	0.21	0.99
Revenue (M €)	39.00	39.00
PROFIT (after 1 year, M €)	**14.22**	**14.69**

The energy cost is higher in the alternative design, but it should be taken into account that electricity is consumed, which is more environmentally friendly than diesel. Maintenance costs are significantly higher in the alternative design due to the cost of battery replacement and the maintenance of RES technologies. Capital costs are higher in the alternative design because of the additional investment in RESs. The costs for property lease, insurance, licensing fee, etc., calculated in the capital costs, are estimated to be 30% of production costs (Quagrainie, 2020). Due to increasing competitiveness in the market, it is assumed that the price of fish will fall by 2% per year. When all revenues and expenses, with a discount rate of 8%, in 20 years of production are calculated, the *NPV* is obtained. From the positive value of the *NPV,* it can be concluded that revenue is high enough to cover the production costs and to achieve a profit, Figure 12.

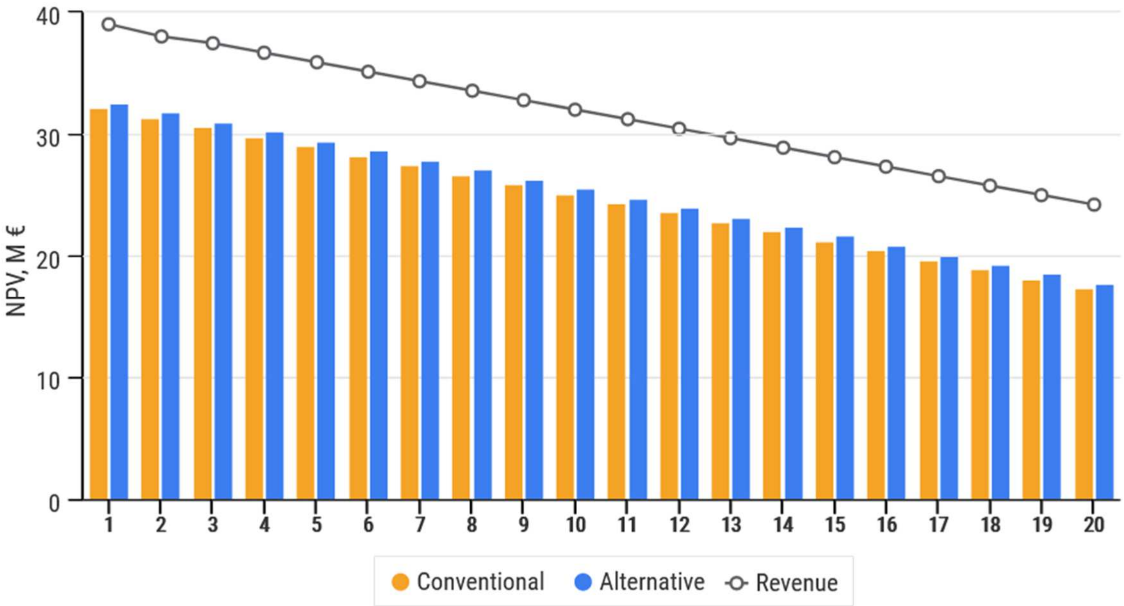

Figure 12. The *NPV* of conventional and alternative mariculture systems

Since many parameters have an impact on costs and, therefore, on profitability, a sensitivity analysis of the *NPV* was performed, Figure 13, where a change in the *NPV* depending on the capital cost, the price of fish feed, and the price of electricity is presented. The values show that the *NPV* remains positive for both conventional and alternative mariculture systems, regardless of the variable changes.

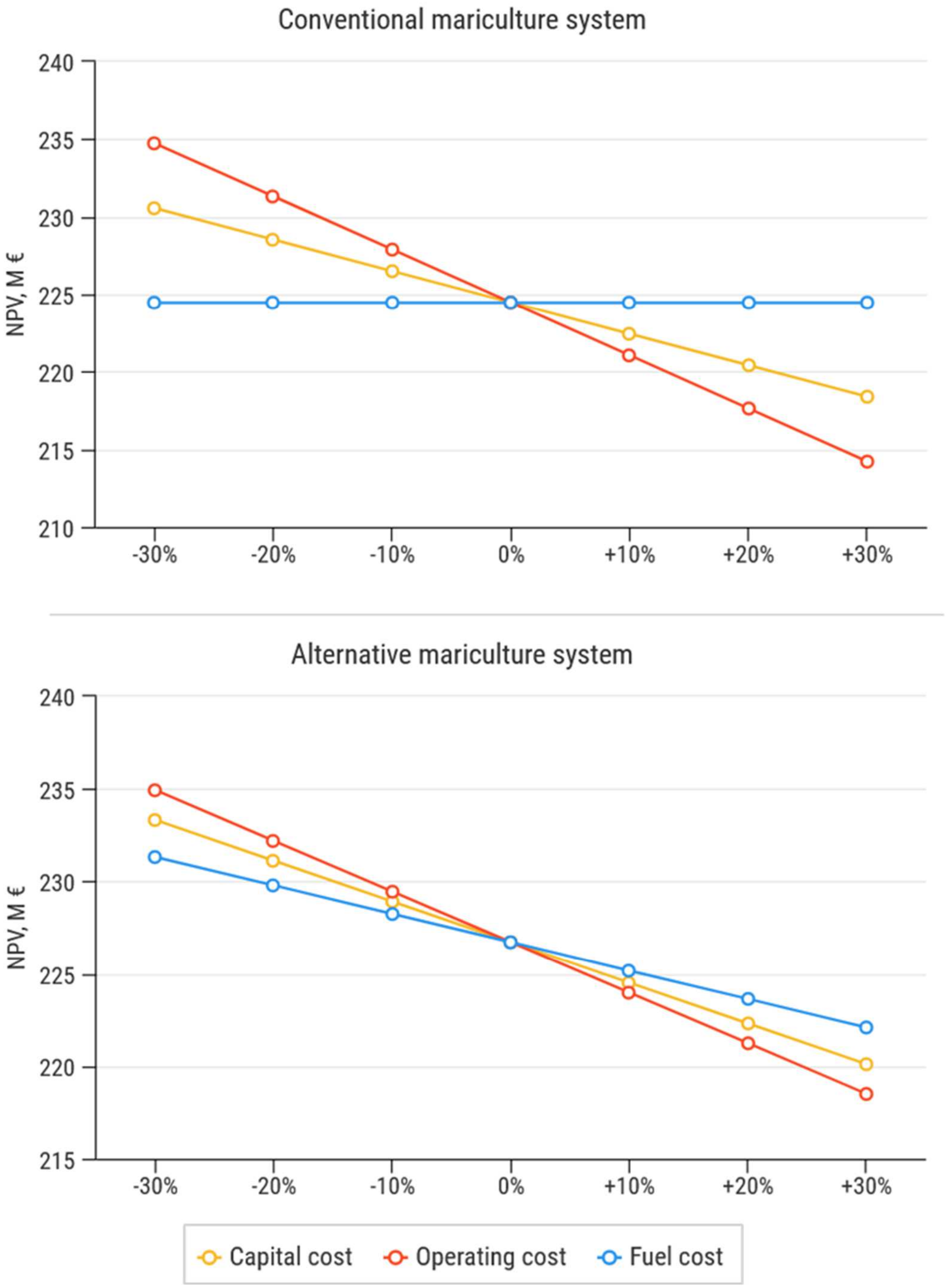

Figure 13. The sensitivity of the *NPV* with respect to different costs

The main difference between conventional and alternative mariculture systems is seen in the fuel cost. The conventional use of diesel seeks to be replaced by electricity, so the change in the price of diesel was not taken into account. If the electricity price decreases by 30%, the *NPV* of the electrified system could rise by 3%, but if the price increases by 20%, the profitability of the alternative farm design is 0.37% lower than in the case of the conventional farm.

5 DISCUSSION

The LCA indicates that a CF reduction is possible in the case of electrification and that there are several ways to achieve a further reduction. Analysis of the mariculture barge shows low values of CF, but there is the possibility of a greater reduction if more wind or solar technologies are installed. For example, if 10 m^2 of surface area for the installation of PV modules is added, the PTW emissions would decline by an additional 0.58% and, simultaneously, the cost of investment and maintenance of the PV modules would rise by 1.41% with a sharper growth, Figure 14. If the surface increases by 100 m^2, the PTW emissions would fall by 5.96% but the cost of the PV system would increase by 12.50%. Since the NPV analysis shows that the difference in profitability between conventional and alternative farms is only 4%, a larger investment in RESs could cause unprofitability.

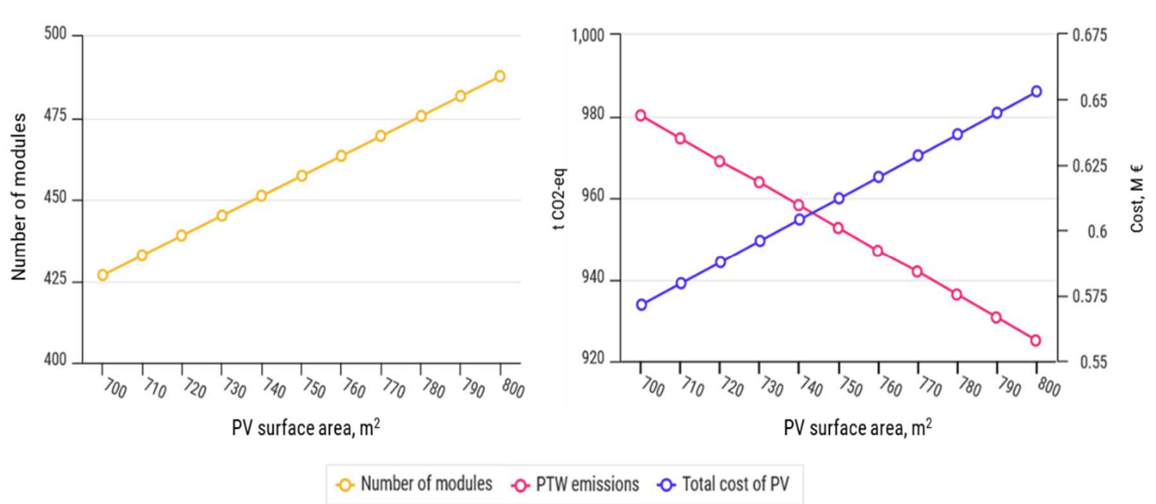

Figure 14. Impact of an increase of PV surface area on emissions and total cost of PV installation

Besides the forms of renewables considered above, sea energy technologies offer energy from waves and tidal currents. As mentioned by Hadžić et al. (2018), tidal converters can be sited near the coastline or on the open sea, which makes them convenient for integration in mariculture. Sea currents are highly predictable, which simplifies their design, but there are several drawbacks, such as the corrosive sea environment, sea fouling and underwater noise, which need to be properly dealt with (Hadžić et al., 2014). Moreover, investigation of the potential of RESs in the Adriatic Sea for use in shipyard processes as presented in (Hadžić et al., 2014) indicates that investment costs in tidal turbines range from €3,825/kW to €12,155/kW, and investment costs in oscillating energy systems range from €5,270/kW to €13,685/kW. Comparisons with the claimed investment costs in solar energy of €2,125/kW and wind energy ranging from €1,700/kW to €4,250/kW associated with small current velocities in the Adriatic Sea (Hadžić et al., 2018), leading to the low efficiency of tidal devices, indicate the low potential of ocean energy in Croatia. For instance, Hadžić et al. (2018) estimated that for an annual production of 20 GWh, approximately 4,450 tidal turbines need to be installed while the same energy can be produced using only five wind turbines of an installed power of 5 MW. The low potential of sea current energy, as well as wave energy in the Mediterranean Sea, is also confirmed by Soukissian et al. (2017), and therefore their use in the mariculture sector in Croatia does not seem viable.

In the alternative mariculture system design, energy costs are 12.81% higher than in the conventional design. Capital costs are also 0.61% higher and include fixed costs that do not depend on the alternation of different economic inputs, such as energy prices, operating costs, salaries, etc. Therefore, the capital cost is affected by possible changes in the price of cages and vessels. By optimizing the mariculture system, the fishing fleet may be further reduced, perhaps even by 50%, which could reduce the total costs. Management expenditures mentioned previously could be reduced, e.g. if state incentives are available, or expenditures could increase if insurance or licensing rates rise. Maintenance costs are approximately four times higher in the alternative design, because of the need for battery replacement and the maintenance of RES technologies. The most significant expenditure in the mariculture system is the price of fish feed. Handfeeding is often performed by an inexperienced worker who lacks technical knowledge. By implementing an automated feeder and monitoring system into a mariculture farm, the feed consumption is controlled and reduces the annual operating costs by about 20% (Shipton and Hasan, 2013). Despite the demands from aquaculture farmers for lower feed prices, further increases are expected and therefore an increase in operating costs can be foreseen (FAO, 2020). This is one of the main reasons why monitoring and automation are introduced into the feeding system. Alternative farm designs achieve higher profit due to the reduction in food consumption.

A comparison of the analysed alternative model with an existing aquaculture system, such as land-based freshwater aquaculture, is also interesting. Roque d'Orbcastel et al. (2009) evaluated a trout production system from a farm that uses a flow-through system (also known as raceway system). In comparison to the presented mariculture farm in this paper, the raceway system does not require vessels for fish handling or feeding, but needs equipment such as mechanical filters and an aeration system which creates an environmental impact. Even though land-based systems eliminate vessels as a significant source of pollution, the infrastructure and high energy needs result in emissions, and the additional demand for water creates an environmental problem that does not appear in mariculture (Roque d'Orbcastel et al., 2009).

The assumptions and limitations of the study, which could be further discussed in order to achieve even more precise results, are the following:

- In the LCA and LCCA, the final disposal stage of the product is not considered, assuming that its contribution on a global scale is not only small, but also similar for both conventional and alternative systems.

- In the LCA, a simplified diesel pathway in the WTP is taken into account, and the results rely on the European energy mix (as usual in an analysis of this type). Somewhat different results can be achieved if a local energy mix is used, but this is slightly impractical because of its relatively high variations compared to the used option.
- In the modelling of economic and environmental performance, it is assumed that carbon tax, which is already an important issue in a number of industries, will not be introduced in the mariculture sector in the near future. If it is introduced, the alternative solutions proposed by the authors will be even more favourable and should be investigated on a scenario-based approach. Such additional expenses can be easily integrated in the proposed LCCA model.

6 CONCLUSION

In this paper, the integral model for the assessment of lifetime emissions and costs for mariculture systems is presented with the aim to contribute economically, ecologically and sustainably to the mariculture sector. The model considers a mariculture barge powered by RESs and a battery-powered workboat. The proposed modifications reduce the CF of mariculture farms in Croatia, entailing a relatively small increase in the investment costs, but leading to higher profitability. Therefore, the integration of RESs in the Croatian mariculture sector is encouraged. Wind and solar power provide many benefits for mariculture, primarily because they do not have the strong impact on the fish farming process itself that sea-power technologies would have.

The main findings obtained by the performed LCA and LCCA can be summarized as follows:

- a total CF reduction of 19.61% for the considered case of a mariculture farm in Croatia;

- an even higher reduction can be achieved if the investigated workboat is replaced with a similar vessel with lower energy consumption;
- the mariculture barge shows a very low amount of CF (21.9% of the total CF of the alternative mariculture system);
- the results of the LCCA show that the alternative design requires only 0.61% greater capital costs than the conventional one;
- with the associated reductions in staff costs and a significant reduction in feed consumption, the profitability of an alternative farm would be 4% higher than that of a conventional farm;
- mariculture farms do not emit high levels of GHGs, but the obtained reduction, although low, would have a positive impact on the environment.

Further research could be related to the application of optimization techniques to determine the proper share of different energy sources related to the mariculture barge for different locations. Alternative solutions could also be considered in the case of inland aquaculture farms to check the viability of the further use of RESs for powering aeration and recirculating systems.

Besides the analysed tuna farm, many fishing and aquaculture companies in the Croatian fishing sector work with an obsolete fishing fleet. Therefore, special attention should be paid to modernizing the power system of ships to achieve further financial savings and environmental benefits. Mariculture and fish catches are closely linked and are often intertwined, which is why this research should be extended to the entire fishing fleet. These results can be further used to optimize the aquaculture sector and greatly reduce GHG emissions.

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