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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

<i>A</i>	area (m ²)
<i>BC</i>	battery capacity (kWh)
<i>BP</i>	battery price (€)
<i>BSE</i>	battery's specific energy (kWh/kg)
<i>BW</i>	battery weight (kg)
<i>C</i>	discounted annual cashflow (€)
<i>D</i>	diameter (m)
<i>d</i>	day
<i>DP</i>	diesel price (€)
<i>EC</i>	energy consumption (kWh)
<i>EF</i>	emission factor (g emission/kg fuel)
<i>FC</i>	fuel consumption (kg/h)
<i>i</i>	time of cash flow (year)
<i>IC</i>	investment cost (€)
<i>LCFC</i>	Life-Cycle Fuel Cost (€)
<i>LCMC</i>	Life-Cycle Maintenance Cost (€)
<i>n</i>	lifetime (year)
<i>NPV</i>	Net Present Value (€)
<i>P</i>	power (kW)
<i>r</i>	discount rate (%)
<i>SFC</i>	specific fuel consumption (kg/kWh)
<i>TE</i>	tailpipe emission (kg/h)
<i>t_s</i>	daily sun hours (h)
<i>v</i>	wind speed (m/s)

Subscripts

<i>A</i>	annual
<i>B</i>	battery-powered ship
<i>D</i>	diesel-powered ship
<i>rad</i>	irradiation
<i>s</i>	sun
<i>w</i>	wind

Abbreviations

CF	Carbon Footprint
EU	European Union
FAO	Food and Agriculture Organization
GHG	Greenhouse Gas
GWP	Global Warming Potential
IEA	International Energy Agency
IMO	International Maritime Organization
LCA	Life-Cycle Assessment
LCCA	Life-Cycle Cost Assessment
ME	Manufacturing emissions
PTW	Pump-to-Wake
PV	Photovoltaic
RES	Renewable Energy Source
WTP	Well-to-Pump
WTW	Well-to-Wake

η	efficiency (-)
ρ	density (kg/m ³)

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35 **1 INTRODUCTION**

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

54

55 **1.1 State of the art in fish farming**

56 Aquaculture is a wide area that can be divided according to different criteria. The basic
57 division is seawater and freshwater aquaculture, depending on the level of salinity of the
58 habitat. Another example of differentiation is water-based, land-based, recirculating and

59 integrated farming systems. Each technique requires a thorough decision-making process to
60 design a quality farming system (FAO, 1987). Typical mariculture systems consist of cages,
61 fishing vessels and an onshore energy network. In the majority of fishing vessels, energy is
62 supplied by fossil fuels, which create a major environmental problem due to the harmful
63 emissions generated by their combustion (Parker et al., 2015).

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

77 Bohnes and Laurent (2020) conducted a detailed analysis of the environmental impact of
78 mariculture production. The study included the impact of the infrastructure itself (materials,
79 chemicals, nutrients, etc.), as well as the impact of feed decomposition and overall energy
80 use. The infrastructural materials in prolonged contact with salt water can decompose and
81 release harmful chemicals, especially the surface layers on which various antifouling coatings
82 are most often found. However, fish feed and energy have the greatest environmental impact.
83 Uncontrolled feeding creates an environmental problem by depositing uneaten feed on the

84 seabed and impacting the growth of marine flora, while feed production and transportation
85 itself result in Greenhouse Gas (GHGs) emissions, as well as other emissions. Automated
86 feeders, monitoring systems, sensors and other equipment help control environmental
87 conditions but increase the energy needs of the farms (Winther et al., 2020).

88 GHGs emissions refer to the emissions of carbon dioxide (CO₂), methane (CH₄), nitrous
89 oxide (N₂O) and fluorinated gases, in low concentrations. These emissions cause the
90 greenhouse effect, which results in the warming of the Earth's surface, causing climate
91 change (UNFCCC, 2021). One of the latest climate agreements is the Paris Agreement (2016)
92 which aims to keep the global temperature rise below 2°C above the pre-industrial level and
93 limit the temperature increase to 1.5°C (UNFCCC, 2021). Considering that the high
94 concentration of CO₂ in the atmosphere greatly contributes to global warming, following the
95 United Nations stance, all industrial sectors should contribute to reducing their Carbon
96 Footprint (CF), including the marine sector, even though it generates a small share of global
97 CO₂ emissions compared to land transport (IMO, 2014). The term CF represents a measure of
98 the total amount of CO₂ emissions that are directly and indirectly caused by an activity or are
99 accumulated over the life stages of a product. The CF can be expressed in tonnes of CO₂ or
100 tonnes of CO₂ equivalent (CO₂-eq) (Wiedmann and Minx, 2008).

101 Several research projects have already been undertaken on replacing fossil fuels as the
102 main energy source in mariculture. Mok and Gaziulusoy (2018) investigated a salmon trout
103 mariculture farm in Finland. They developed a strategic design framework focused on
104 anticipating and mitigating foreseeable problems, such as industrial pollution. Another
105 perspective is given by Ton Nu Hai et al. (2020), who stated that the environmental impact of
106 a mariculture farm is influenced not only by the production process but also by the production
107 environment. In their case study, they compared two lobster farms located in Vietnam and
108 concluded that various parameters, from nutrient input to farm size and the distance between

109 two farms, have a major impact on their environmental footprint. Especially high levels of CF
110 can be found on a shrimp farm, due to the emissions of commercial and biological feed and
111 the use of different substances for improving water quality (Chang et al., 2017). They
112 emphasized the importance of integrating energy-conserving technology in aquaculture to
113 reduce the CF. A common assessment tool used in the mentioned studies is the Life-Cycle
114 Assessment (LCA), which is used to estimate emissions through a product's lifecycle (Chang
115 et al., 2017). In general, the reduction of the CF in the context of an aquaculture farm can be
116 achieved in various ways, including by integrating RESs into the system.

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

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

134 could drive sensors and devices for monitoring and controlling the growing conditions
135 (nutrients, temperature, pH, salinity, turbidity, etc.), oxygenation manipulation, and lighting.

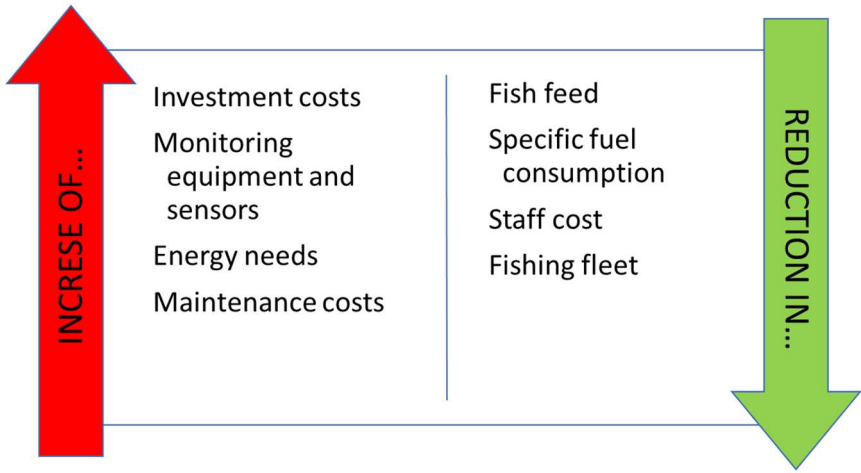
136 The exploitation of wind energy has significantly increased in recent years, especially in
137 Northern Europe. Although similar technology is used for onshore wind farms as for inland
138 ones, costs are increased due to difficult environmental conditions. Hadžić et al. (2014)
139 presented an overview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

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

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

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

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



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173

174

Figure 1. The impact of mariculture modernization on total costs

175 **1.2 Research gap, aim and contribution of the paper**

176 After an extensive literature review (over 200 publications), Badiola et al. (2018)
177 emphasized the significance of determining the environmental impact of mariculture
178 production and the need for improvement. As they stated, previous works dealing with
179 sustainable production often did not include energy use and the economic and environmental
180 impacts of production, especially in the mariculture sector. The replacement of fossil fuels by
181 RESs is currently a trending topic in other industries (e.g. land transport), but research on
182 their integration in mariculture is underrepresented. This paper seeks to find suitable solutions
183 to the above problems using the example of a water-based mariculture farming system.
184 Recently, Le Féon et al. (2021) presented a multi-attribute model called DEXiAqua for the
185 assessment of sustainability of aquaculture systems via several indicators from technical
186 domains and reference methods, among which life-cycle emissions and life-cycle costs play
187 an important role. The model was applied to a case study of salmon Farming in France.
188 However, Le Féon et al. (2021) indicate that more studies related to other systems with
189 different technical properties and put in different context are desirable for future refinements
190 of the model. Assessment of environmental impact of aquaculture projects in Chile between
191 1994 and 2019 presented by Rodríguez-Luna et al. (2021) belongs to this category of studies,
192 where opportunities to improve environmental indicators of aquaculture systems are
193 indicated.

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

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

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

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

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

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

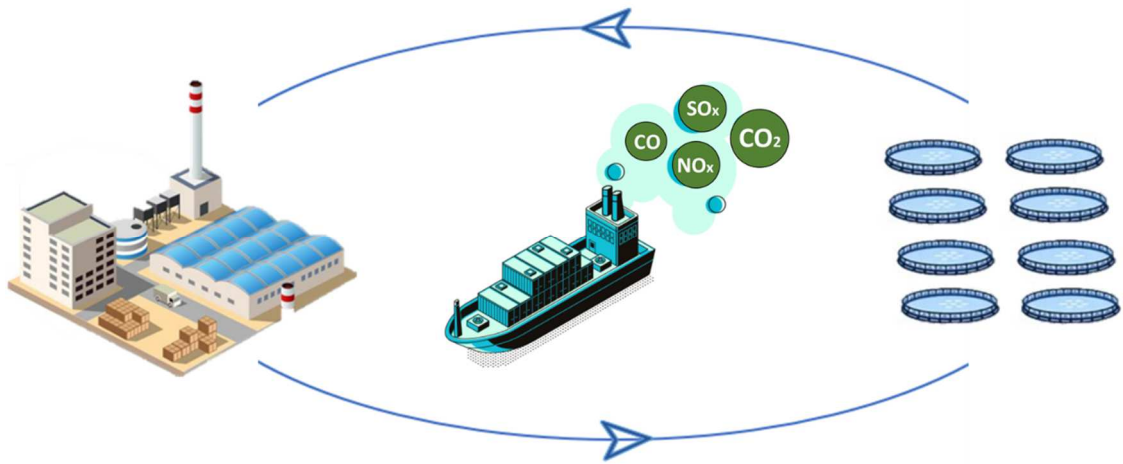
224 The original contribution of this paper includes:

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

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

235 **2 METHODOLOGY**

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



241

242

Figure 2. Model of a conventional mariculture system

243

244

By modernizing the farms, i.e. installing automated feeders and monitoring systems, the

245

need for vessels declines as equipment is relocated onto a mariculture barge, Figure 3. The

246

idea is to fully electrify the workboats and power the barge by using solar and wind energy,

247

integrated with diesel generators.



248

249

Figure 3. Model of an electrified mariculture system

250

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

254

255 **2.1 LCA**

256 An LCA investigates the environmental impact of a system. In this paper, by using the
257 LCA software GREET (2020), a comparative analysis is conducted with the focus on the
258 CO₂-eq emissions released throughout life cycle of the system. The focus is on the emissions
259 related to the power system, where they are analysed in the following phases:

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

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

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

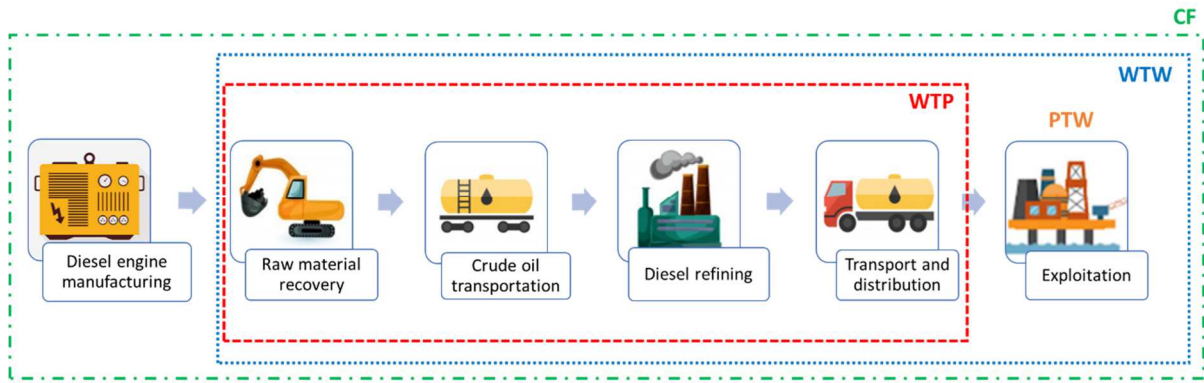
274 Diesel-powered systems include processes from diesel-engine manufacturing to diesel
275 combustion in the engine. The process can be divided into phases, as presented in Figure 4.
276 The Well-to-Wake (WTW) phase relates to emissions released from the processes in the WTP
277 phase and the process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

$$TE = FC \cdot EF, \quad (1)$$

284 where FC represents the fuel consumption in kg/h and EF denotes the emission factor in kg
285 gas/kg fuel. The GHG emissions factors for diesel are obtained from (IMO, 2014). For this
286 calculation, the SFC of a diesel-powered vessel is assumed to be 0.215 kg/kWh (Perčić et al.,
287 2020a). GHGs released during the combustion of diesel can be quantified as presented in the
288 following Eq. (2) (Perčić et al., 2020b):

$$CF = GWP_{CO_2} \cdot TE_{CO_2} + GWP_{CH_4} \cdot TE_{CH_4} + GWP_{N_2O} \cdot TE_{N_2O}, \quad (2)$$

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



294

295

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

296

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

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

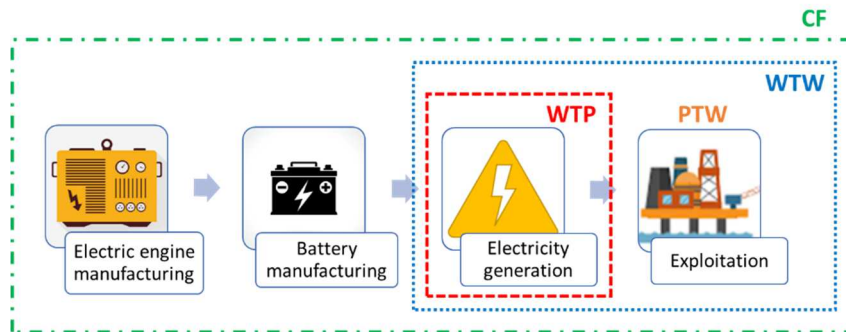
303 When the battery degradation and safety requirements are calculated in, the required
 304 capacities are increased by 50%.

305 The LCA of a battery-powered system configuration includes the manufacturing processes
 306 of an electric engine and the battery and the electricity generation process, presented in Figure
 307 5. The energy density of a Li-ion battery with nickel manganese cobalt oxide (NMC) is 0.15-
 308 0.22 kWh/kg (Perčić et al., 2020b). To analyse the environmental impact of the battery, the
 309 weight of the battery, BW (kg), is calculated as in Eq. (4):

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

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

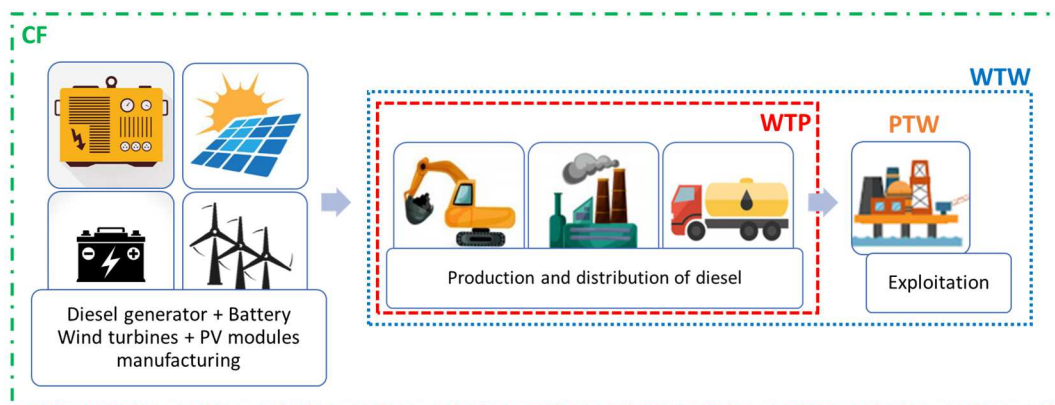
311 Another significant input is the replacement of the battery, which is assumed to be every
312 10 years. The environmental footprint of an electric engine is assumed to be equal to the
313 environmental footprint of a diesel engine. The electricity generation process is affected by
314 the national electricity mix of the country for which it is being investigated.



315
316 Figure 5. Processes included in the LCA of a battery-powered system

317

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



322
323 Figure 6. Processes included in the LCA of a wind-PV cells powered system

324

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

$$E_{PV} = \eta_{PV} \cdot E_{rad} \cdot A, \quad (5)$$

328 where η_{PV} represents the efficiency of the PV system, E_{rad} (MJ/m²) denotes the average solar
329 irradiance, and A (m²) denotes the area covered by the PV cells. By dividing the calculated
330 E_{PV} with the number of daily sun hours t_s (h), the power output of a PV system P_{PV} (kWh) is
331 determined.

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

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

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

339 where ρ (kg/m³) denotes the air density, A_w (m²) denotes the swept area, i.e. the area of a
340 wind turbine, and v denotes (m/s) the wind speed. The area of a wind turbine can also be
341 calculated as in Eq. (7):

$$A_w = \frac{D^2 \cdot \pi}{4}, \quad (7)$$

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

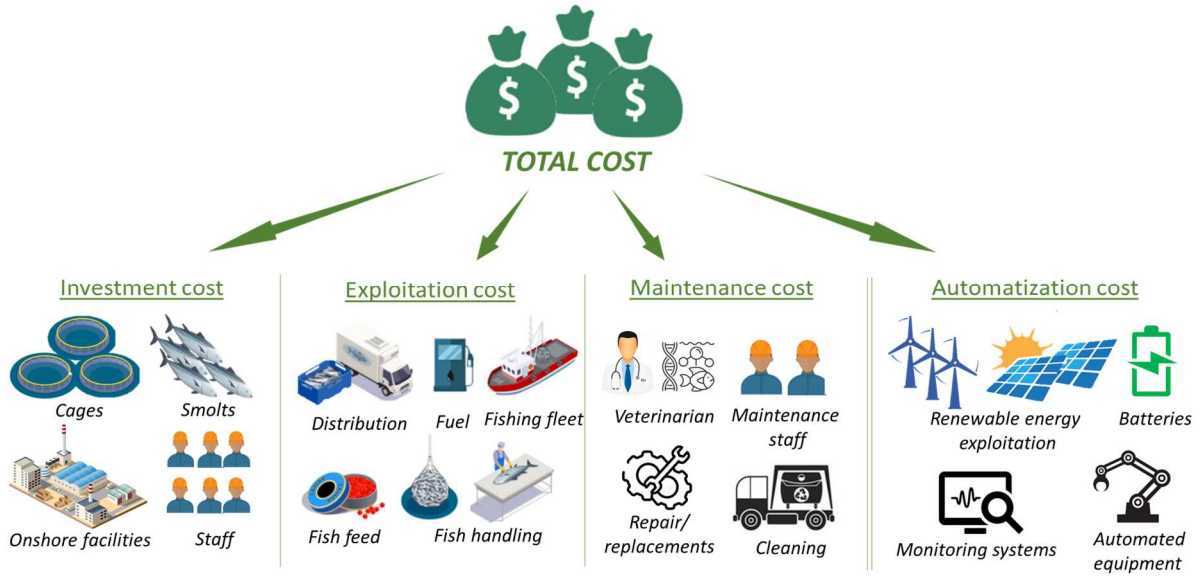
343 The manufacturing process of wind turbines includes the weight of the materials from
344 which they are constituted (Wang et al., 2017).

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

348

349 **2.2 LCCA**

350 An LCCA includes the total life-cycle costs of a system, e.g. the investment cost, the cost
351 of fuel, maintenance costs, and other costs. Due to the expected introduction of carbon
352 allowance in the future, i.e. the cost of a permit to emit CO₂, it is useful to calculate the cost-
353 effectiveness of a different power system (Perčić et al., 2020b). The total costs of a
354 mariculture system design are presented in Figure 7. The investment cost includes the capital
355 costs of mariculture cages and the establishment of onshore facilities. The costs also include
356 the price of fingerlings or smolts and staff wages. Exploitation costs include the costs of fuel
357 consumed in the power system (transportation, distribution, fish handling), staff wages and
358 the equipment needed for fish handling, and the cost of fish feed. Maintenance costs include
359 different repairs, equipment replacement costs, veterinarians, maintenance staff, and similar.
360 The last group covers the costs of farm automatization. These costs include the price of the
361 installation of renewables, batteries and their replacement, and automated equipment.



362

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Figure 7. Total costs of a mariculture farming system

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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):

$$LCFC_D = FC \cdot DP, \quad (8)$$

369

370

371

372

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 ($LCMC_D$).

373

374

375

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.

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

$$IC_B = \frac{BC \cdot BP}{0.45}, \quad (9)$$

378 where BC denotes the battery capacity calculated according to eq. (3) and BP denotes the
379 battery price. The $LCFC_B$ is determined by the energy consumption of a battery-powered
380 vessel and the electricity cost (€/kWh), while the $LCMC_B$ depends on the battery capacity and
381 the battery price anticipated after 10 years, which is assumed to be €169/kWh, Perčić et al.
382 (2020b).

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

392

393 **2.3 Assessment of project profitability**

394 To gain a complete insight into the system of RESs and its possible modifications, a
395 technical and economic analysis of the system was conducted. By changing the technical
396 characteristics of the system, such as wind speed, number of sunny hours, but also economic

397 features such as the price of electricity, the net present value (*NPV*) changes. The *NPV* is
398 calculated by the following Eq. (10) (Di Trapani et al., 2014):

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

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

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

405

406 **3 CASE STUDY**

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

414 The investigated location, presented in Figure 8, shows favourable energy characteristics
415 for the use of RESs. Zadar is known for a large number of sunny hours t_s (h) throughout the
416 year, and the horizontal irradiation is determined at 5,471 MJ/m²/year (Global Solar Atlas,
417 2021). The wind velocity is the highest during the night, while during the day it may achieve

418 minimal values, especially during the summer. Farkas et al. (2019) indicated the “Jugo” and
419 “Bora” as the most significant winds that can affect the annual amount of energy produced in
420 Croatia. The mountainous area in the Croatian Littoral also has a great influence: it
421 accelerates the winds which slow down as they approach the coast. For the purpose of this
422 paper, the average velocity of 6.5 m/s is used in the calculation according to Hadžić et al.
423 (2014). The wind density at an ambient temperature of 20°C is 1.2 kg/m³.



424

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

426

427 The investigated mariculture system consists of 22 cages with a diameter of 50 metres. The
428 cage cost is set according to Rubino (2008), who determined a value of \$30 per m³ (approx.
429 €25/m³). The volume of the investigated farm is around 25,000 m³ per cage. Therefore, the
430 price is assumed to be €625,000 per cage. Maintenance of the cages is performed twice a
431 year, using a net cleaner whose rental cost is estimated at around €25,000, including fuel
432 consumption (Osterbo Gruppa, 2021). The staff is estimated to amount to six persons per

433 cage, according to FAO (2020). The average monthly gross earning in Croatia is approx.
434 €1,100 (Croatian Bureau of Statistics, 2021), which is adopted as the monthly payment cost
435 per person in this paper. Veterinarians are also a necessary part of the staff and their monthly
436 payment is estimated at €1,700/month.

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

449 The investment cost of establishing a fish farm can be quite high (Šteko, 2019). Firstly,
450 30,000 fingerlings are procured. According to the data available on Eurofish (2021),
451 procurement is usually performed by catching specimens (8-10 kg per fish) which requires a
452 weekly cost of vessels and staff (estimated at €400). It is assumed that spawn procurement is
453 performed twice a year, with an average duration of four weeks. According to FAO (2020),
454 fish feed accounts for almost 50% of the total production cost. The cultivation of tuna
455 requires 17 kg of feed per kg of fish a day. The fish are fed for 20-25 days monthly. By
456 multiplying the required quantity with the number of specimens in a farm and the average fish
457 weight, the amount of feed needed in a month can be calculated. After a market analysis, the

458 cost is assumed to be €1.05/kg of feed. The cost per kg is assumed to be relatively low
 459 because, to the best of the authors' knowledge, the Croatian market is saturated with small
 460 finfish which is why it achieves a low wholesale price. The price of full-grown specimens
 461 (around 40 kg) is estimated at €30/kg (Sea Food Source, 2020). The annual overall
 462 production is approx. 1,300 tonnes of tuna.

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

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

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

470

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

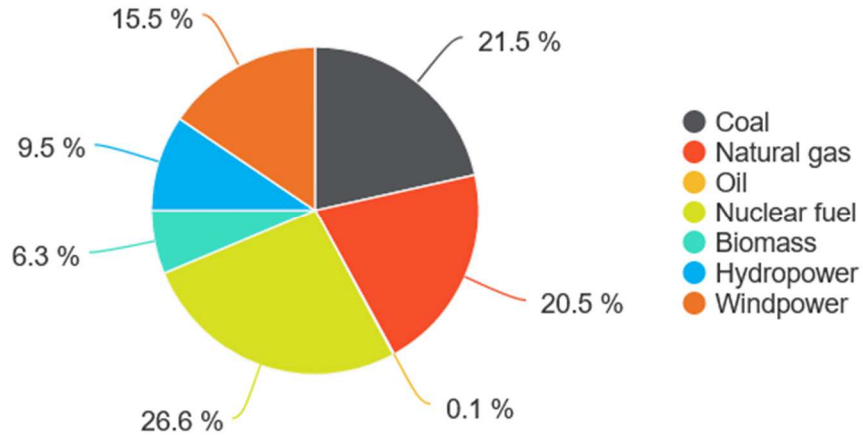


Figure 9. European electricity mix, GREET (2020)

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476

477

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

484

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			

485

486 4 RESULTS

487 The results of the LCA and LCCA, performed for a conventional and an alternative
 488 mariculture farm design, are presented in Figures 10 and 11. The LCA of a conventional
 489 mariculture farm shows a high CF. When compared to the LCA results of an alternative

490 mariculture farm, a CF reduction of 19.62% is achieved by electrification. The majority of
 491 emissions in the alternative design is related to electricity production and the calculated
 492 amounts are directly dependent on the electricity mix used, i.e. by raising the share of RES in
 493 the electricity mix, a positive impact on emission reduction would be achieved. In the
 494 alternative mariculture system, 21.9% of the total CF is generated by the barge, while the
 495 remaining 78.1% is generated by the workboat, Figure 10 – right-hand graph.

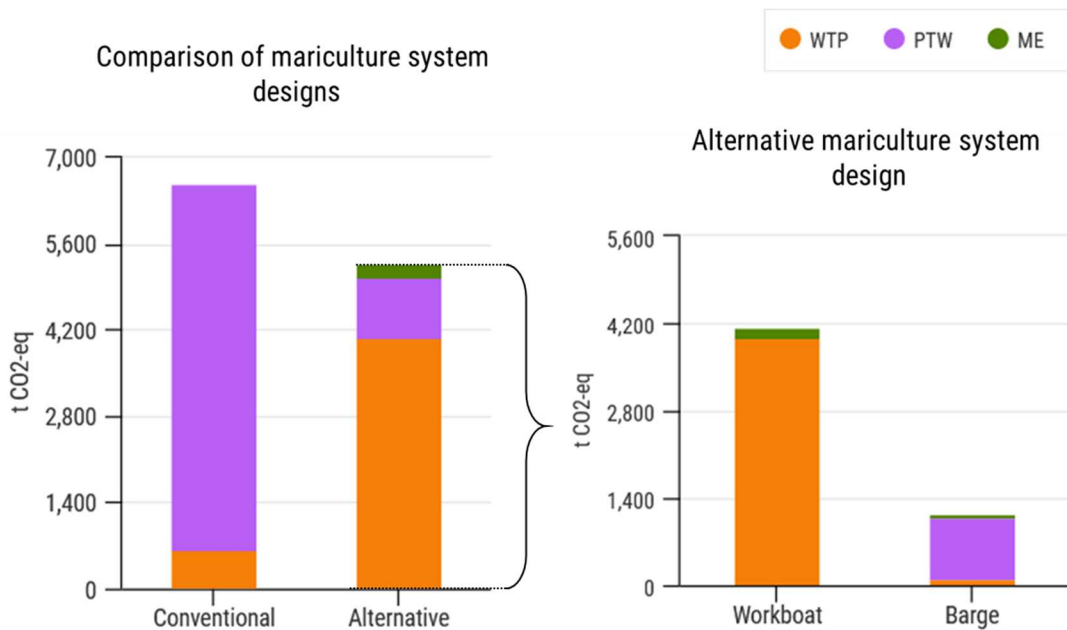


Figure 10. The LCA results

496
 497
 498

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

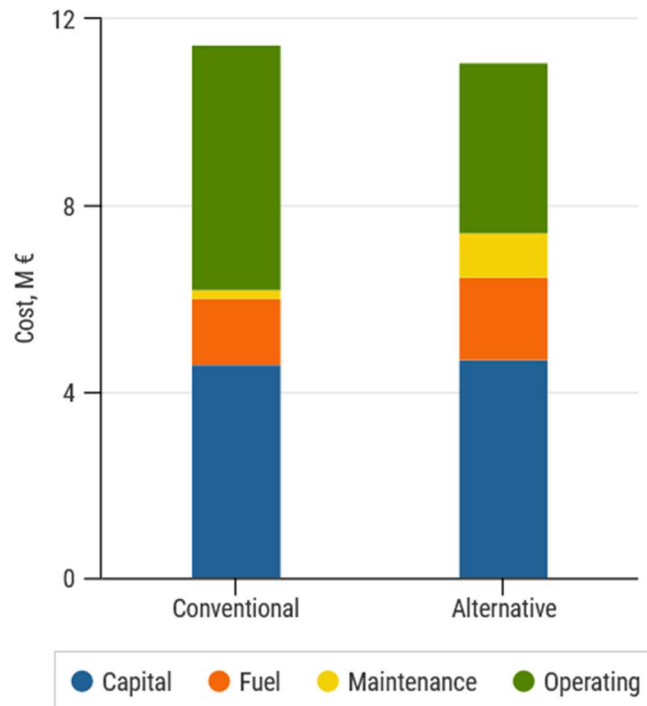


Figure 11. The LCCA results

503
504
505

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

509

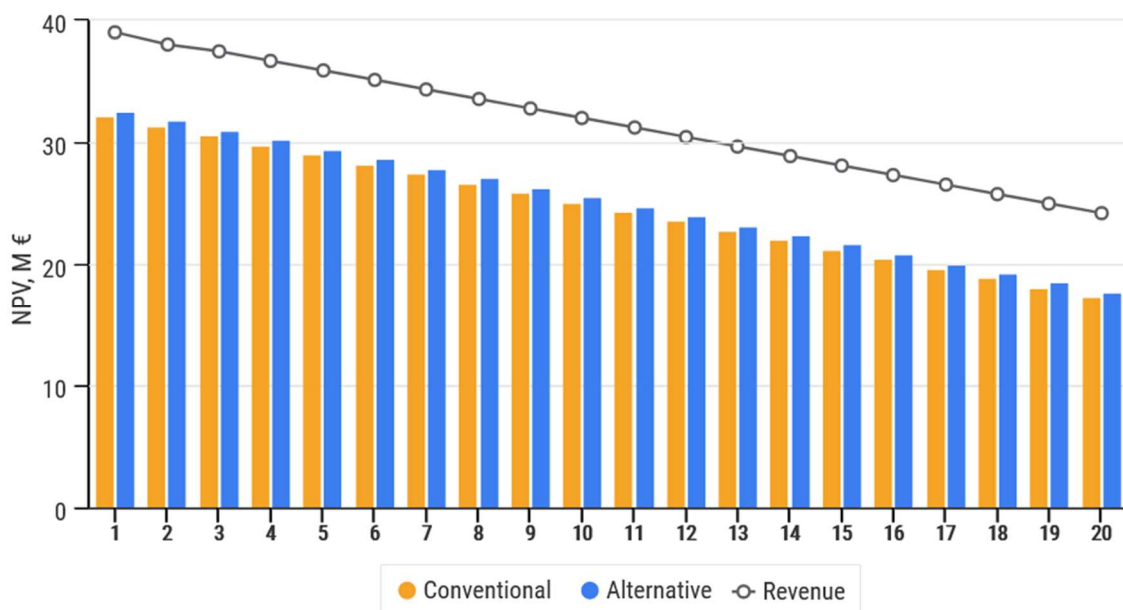
Table 3. Financial plan of a mariculture farm (after 1 year)

	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

510

511 The energy cost is higher in the alternative design, but it should be taken into account that
512 electricity is consumed, which is more environmentally friendly than diesel. Maintenance
513 costs are significantly higher in the alternative design due to the cost of battery replacement
514 and the maintenance of RES technologies. Capital costs are higher in the alternative design

515 because of the additional investment in RESs. The costs for property lease, insurance,
 516 licensing fee, etc., calculated in the capital costs, are estimated to be 30% of production costs
 517 (Quagraine, 2020). Due to increasing competitiveness in the market, it is assumed that the
 518 price of fish will fall by 2% per year. When all revenues and expenses, with a discount rate of
 519 8%, in 20 years of production are calculated, the *NPV* is obtained. From the positive value of
 520 the *NPV*, it can be concluded that revenue is high enough to cover the production costs and to
 521 achieve a profit, Figure 12.



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

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

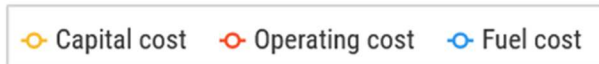
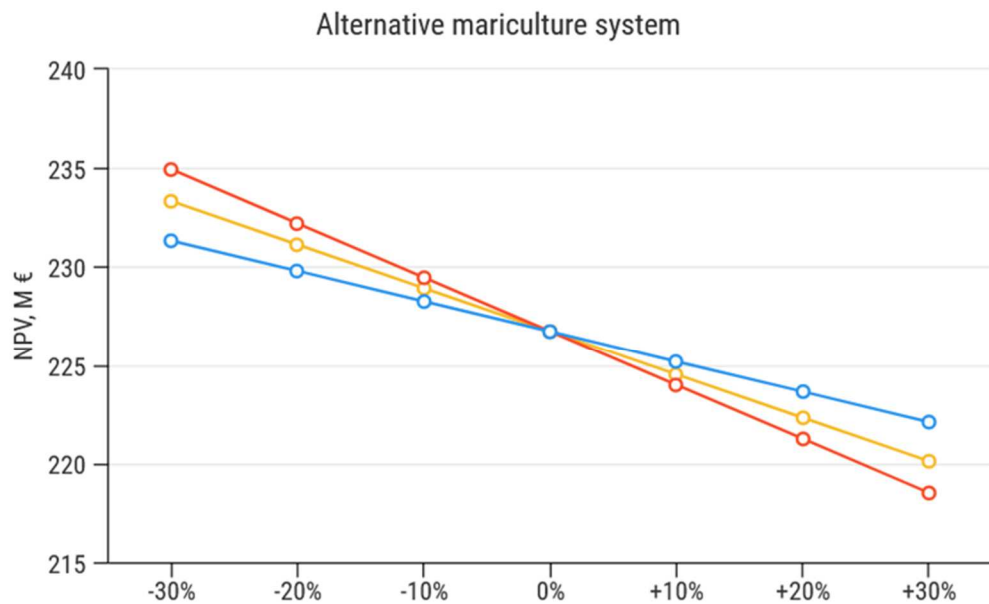
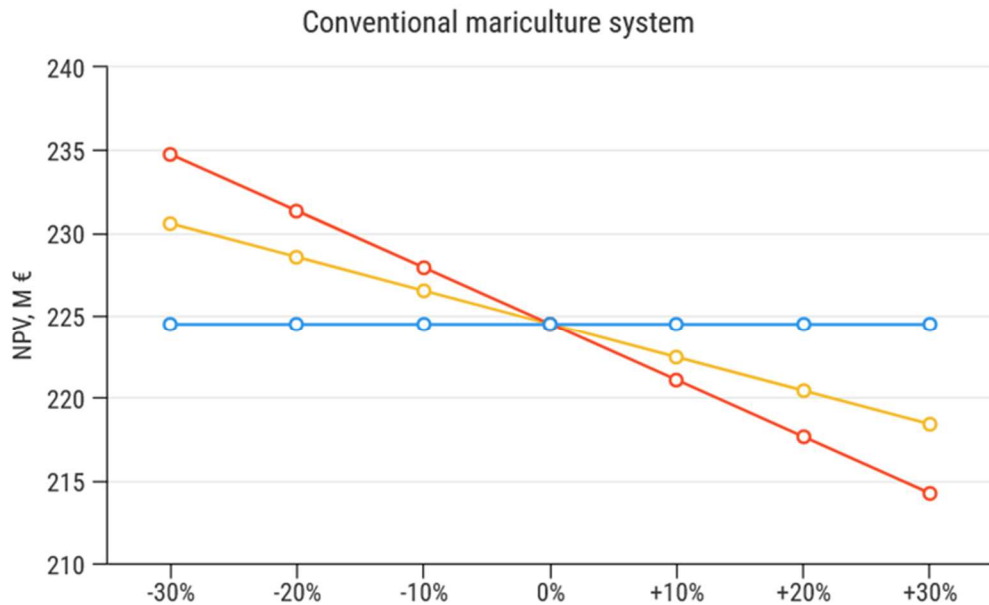


Figure 13. The sensitivity of the *NPV* with respect to different costs

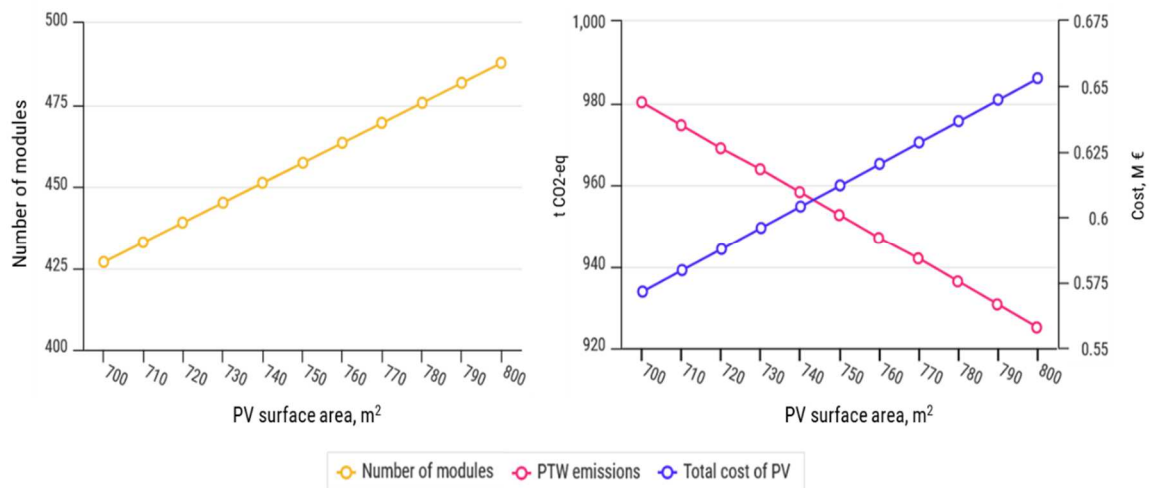
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532

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

537 profitability of the alternative farm design is 0.37% lower than in the case of the conventional
538 farm.

539 5 DISCUSSION

540 The LCA indicates that a CF reduction is possible in the case of electrification and that
541 there are several ways to achieve a further reduction. Analysis of the mariculture barge shows
542 low values of CF, but there is the possibility of a greater reduction if more wind or solar
543 technologies are installed. For example, if 10 m² of surface area for the installation of PV
544 modules is added, the PTW emissions would decline by an additional 0.58% and,
545 simultaneously, the cost of investment and maintenance of the PV modules would rise by
546 1.41% with a sharper growth, Figure 14. If the surface increases by 100 m², the PTW
547 emissions would fall by 5.96% but the cost of the PV system would increase by 12.50%.
548 Since the NPV analysis shows that the difference in profitability between conventional and
549 alternative farms is only 4%, a larger investment in RESs could cause unprofitability.



550

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

552

553 Besides the forms of renewables considered above, sea energy technologies offer energy
554 from waves and tidal currents. As mentioned by Hadžić et al. (2018), tidal converters can be

555 sited near the coastline or on the open sea, which makes them convenient for integration in
556 mariculture. Sea currents are highly predictable, which simplifies their design, but there are
557 several drawbacks, such as the corrosive sea environment, sea fouling and underwater noise,
558 which need to be properly dealt with (Hadžić et al., 2014). Moreover, investigation of the
559 potential of RESs in the Adriatic Sea for use in shipyard processes as presented in (Hadžić et
560 al., 2014) indicates that investment costs in tidal turbines range from €3,825/kW to
561 €12,155/kW, and investment costs in oscillating energy systems range from €5,270/kW to
562 €13,685/kW. Comparisons with the claimed investment costs in solar energy of €2,125/kW
563 and wind energy ranging from €1,700/kW to €4,250/kW associated with small current
564 velocities in the Adriatic Sea (Hadžić et al., 2018), leading to the low efficiency of tidal
565 devices, indicate the low potential of ocean energy in Croatia. For instance, Hadžić et al.
566 (2018) estimated that for an annual production of 20 GWh, approximately 4,450 tidal turbines
567 need to be installed while the same energy can be produced using only five wind turbines of
568 an installed power of 5 MW. The low potential of sea current energy, as well as wave energy
569 in the Mediterranean Sea, is also confirmed by Soukissian et al. (2017), and therefore their
570 use in the mariculture sector in Croatia does not seem viable.

571 In the alternative mariculture system design, energy costs are 12.81% higher than in the
572 conventional design. Capital costs are also 0.61% higher and include fixed costs that do not
573 depend on the alternation of different economic inputs, such as energy prices, operating costs,
574 salaries, etc. Therefore, the capital cost is affected by possible changes in the price of cages
575 and vessels. By optimizing the mariculture system, the fishing fleet may be further reduced,
576 perhaps even by 50%, which could reduce the total costs. Management expenditures
577 mentioned previously could be reduced, e.g. if state incentives are available, or expenditures
578 could increase if insurance or licensing rates rise. Maintenance costs are approximately four
579 times higher in the alternative design, because of the need for battery replacement and the

580 maintenance of RES technologies. The most significant expenditure in the mariculture system
581 is the price of fish feed. Handfeeding is often performed by an inexperienced worker who
582 lacks technical knowledge. By implementing an automated feeder and monitoring system into
583 a mariculture farm, the feed consumption is controlled and reduces the annual operating costs
584 by about 20% (Shipton and Hasan, 2013). Despite the demands from aquaculture farmers for
585 lower feed prices, further increases are expected and therefore an increase in operating costs
586 can be foreseen (FAO, 2020). This is one of the main reasons why monitoring and automation
587 are introduced into the feeding system. Alternative farm designs achieve higher profit due to
588 the reduction in food consumption.

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

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

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

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

614

615 **6 CONCLUSION**

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

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

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

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

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

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

651

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