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Energy analysis in fish aquaculture: Cumulative energy demand of different farming systems

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A B S T R A C T

Energy consumption is one of the critical challenges for the continued growth of the aquaculture sector. In addition to the substantial feed consumption common to all types of systems, the high direct energy demand is driven by electricity use for water extraction, pumping, and aeration in land-based farms, and by fuel consumption in coastal farms. The aim of this study is to analyse the Cumulative Energy Demand (CED) of the production of European Sea Bass and Gilthead Sea Bream across different farming systems in the Mediterranean area. By focusing on both land-based and coastal sea-cage systems, an energy analysis of four different farms was conducted using a "from cradle to gate" life cycle approach. The functional unit for this study was set at 1 tonne of fish. The results show that land-based farms have a higher CED (168,535 and 188,642 MJ/t) due to both feed consumption (32 and 39 % of the total) and the use of liquid oxygen (46 and 16 % of the total) and direct electricity (20 and 43 % of the total, with on-site electricity consumption of 34,167.6 and 14,086.8 MJ/t). The lower CED of coastal farms (66,224 and 76,507 MJ/t) is largely due to feed usage (around 90 % of the total) and low fuel intensity (67.6 and 82.9 l/t, corresponding to 2495 and 3057 MJ/t, respectively). A scenario analysis was conducted using the 2030 projected national electricity mix of the Integrated National Energy and Climate Plan for land-based farms. Additionally, the impact of substituting diesel with biofuel in coastal farms was evaluated. The results indicate that these changes could reduce the use of non-renewable sources by at least 5 %.

1. Introduction

Aquaculture has emerged as a pivotal sector in global food production, contributing significantly to the supply of seafood and playing a vital role in food security (FAO, 2024). The rapid expansion of aquaculture has led to an increased focus on the environmental impacts associated with different farming systems. Among these impacts, energy consumption is a key factor, influencing both the sustainability and economic viability of aquaculture operations (Badiola et al., 2017). Energy use in aquaculture varies widely depending on the type of farming system, the species being cultivated, and the geographical location of the farm (Pelletier et al., 2011; Yi et al., 2024).

In Mediterranean aquaculture, European seabass (*Dicentrarchus labrax*, ESB) and Gilthead seabream (*Sparus aurata*, GSB) are two of the most commonly farmed species (Zoli et al., 2024). Economically, these species are significant, together accounting for 26 % of the total economic value of Mediterranean aquaculture, with a combined worth of approximately 3.6 billion USD (FishStatJ, 2024). These species are predominantly raised in either coastal sea-cage systems or land-based facilities, with each system presenting distinct energy requirements. Coastal sea-cage farming is generally considered less energy-intensive due to the reliance on natural water flow for oxygenation and waste removal. In addition, this type of system may also rely on ecosystem services for water quality maintenance. Therefore, typically, the energy consumptions of this type of system are mostly indirect as feed-related energy inputs account for a large proportion of the overall energy profile (Troell et al., 2004); however, fuel consumptions for the management of sea cages cannot be neglected (Pelletier et al., 2011).

In contrast, land-based systems, particularly those employing Recirculating Aquaculture Systems (RAS) or Flow-Through Systems (FTS), often require significant energy inputs for water circulation, aeration, and temperature control. Intensive land-based FTS or RAS are often characterized by substantial energy inputs for activities such as pumping and filtering water. Thus, there are often trade-offs in the nature and extent of environmental impacts associated with open versus closed containment systems. Furthermore, as reported by Henrikkson et al. (2013) there is an expected but imperfect correlation between energy demand and global warming potential, mainly related to feed

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consumption. Although feed-related energy inputs generally represent a large percentage of the overall energy profile of an intensive livestock system, the absolute scale of these inputs is very sensitive to the specific components of the feed used (Troell et al., 2014).

The cumulative energy demand (CED) of a product is the sum of direct and indirect energy, measured in MJ and consumed during its entire life cycle, including extraction, production and disposal of raw and auxiliary materials used. The total CED is composed of the cumulative demand for fossil energy (i.e. from coal, lignite, peat, natural gas and crude oil) and the CED of nuclear, biomass, water, wind and solar energy over the entire life cycle (Huijbregts et al., 2010).

Despite the importance of energy use in aquaculture, few studies have analysed the energy dynamics of aquaculture systems worldwide. Bozoğlu and Ceyhan (2009) examined the energy balance and conversion efficiency of trout and sea bass production in the Black Sea region of Turkey. Rahman and Paramesh et al. (2019) evaluated the energy use and sustainability of "gher farming," a unique integrated system combining prawn, fish, and rice cultivation in Bangladesh's coastal areas. Xu et al. (2022) conducted a combined economic, energy, and life-cycle assessment (LCA) of various rice-fish coculture systems in China, highlighting the trade-offs between economic performance and environmental sustainability. Specifically, there is a lack of detailed studies focusing on the CED of ESB and GSB production in the Mediterranean (Zoli et al., 2023a). While some Life Cycle Assessment (LCA) studies have been conducted on these species also evaluating CED impact category — Zoli et al. (2023b) in a coastal farm in Italy, Abdou et al. (2018) in 24 Tunisian farms, and Jerbi et al. (2012) in raceway systems — no study specifically addressed the energy dynamics within these systems. Understanding the CED is crucial for identifying opportunities to improve the sustainability of aquaculture practices, particularly in the context of rising energy costs and the global shift towards renewable energy sources.

This study aims to fill this gap by analysing and comparing the CED of ESB and GSB production across different farming systems in the Mediterranean area. By focusing on both land-based and coastal sea-cage farms, this research provides a comprehensive assessment of energy use patterns, highlighting the contributions of various energy sources and identifying potential areas for improvement.

2. Materials and methods

2.1. Goal and scope definition

The goal of this study is to analyse in detail the CED of different types of aquaculture farms specializing in the farming of ESB and GSB. Indeed, depending on the type of farming, the energy demand and its characteristics may vary, differ by orders of magnitude, and lead to different outcomes. To build the mass and energy flow characterizing the analysed systems, the Life Cycle Assessment (LCA) approach was applied, following ISO 14040 and 14044 standards (ISO, 2006a, b). This allowed for an in-depth examination of the energy requirements necessary for the farms in question, considering the entire life cycle of all required inputs. This study was conducted on representative ESB and GSB farms in the Mediterranean area and reflects the most traditional farming systems and technologies that characterize the current context of the area of interest. In particular, two coastal farms were analysed, where farming typically takes place in sea floating cages, and the management of the farming process (feeding, disease control, harvesting, etc) is carried out using a fleet of vessels, resulting in fuel consumption. Two land-based farms were also analysed, where fish are typically raised in ponds (either earthen or concrete) characterized by a complex system of generators, pumps, filters, and aerators necessary for water extraction, pumping, oxygenation and flow.

The functional unit (FU) used in the study is 1 tonne of live fish weight, and the approach for defining system boundaries is "from cradle to farm gate." Therefore, all inputs necessary for operations from raw material extraction to fish harvesting were considered. Specifically, as shown in Fig. 1, the fish farming process was divided into 5 subsystems: (I) raw material extraction and production of inputs common to all subsystems; (II) production and supply of juveniles; (III) production, use, maintenance, and end-of-life of infrastructure and equipment; (IV) production and supply of aquafeed; (V) farm management and fish harvesting.

2.2. Description of the analysed farms

Four Italian farms specialising in ESB and GSB breeding were analysed. To this purpose, on-site visits were made to each of the farms and information regarding farm description and management was collected. In particular, two land-based (LF1 and LF2) and two coastal-farms (CF1 and CF2) were analysed.

The first land-based farm (LF1) has a production of about 450 t/year represented by 53 % ESB and 47 % GSB. The farm consists of about 60 concrete and fiberglass tanks, ranging from 30 m^3 to 900 m^3 , with a total area of 88,000 m^2. Juveniles of 6 g and 4.5 g are seeded for ESB and GSB, respectively and grown until they reach the commercial size of 600 g. The average Economic Feed Conversion Ratio (eFCR = kg of distributed feed per kg of live fish weight harvested, Aubin et al., 2009) for the production is 2.61. This farm, located on the coast, pumps seawater directly into all tanks.

The second land-based farm (LF2) produces around 460 t/year (39 % ESB and 61 % GSB) annually in a total area of 150,000 m^2 with 50 ponds of various sizes, from 75 to 550 m^3 . The 3 g juveniles are seeded in specific ponds and then transferred to other ponds up to the commercial size of 400–600 g. The average eFCR characterising production is 2.4. This farm extracts groundwater from an aquifer at a depth of about 40 m, which is energy-intensive but guarantees stable temperature, salinity and pathogen-free conditions throughout the year.

The first coastal farm (CF1) analysed is a large Italian farm. The average annual production of the farm is about 1800 t, divided approximately 50 %-50 % between ESB and GSB. The farm consists of 32 sea cages of various sizes, with an average of 10,000 m^3 each, located about 4 miles offshore. The eFCR for the year analysed is 2.16, averaged between the two species. Further details on the farm can be found in Zoli et al. (2023b).

The second coastal farm (CF2) has an annual production of about 1300 t (46 % ESB and 54 % GSB). It comprises 44 sea cages of different sizes, ranging from 2000 m^3 to 9000 m^3 , with an average volume of 6000 m^3 , and a total area of about 2000,000 m^2. Juveniles of 4.5 g and 6 g are seeded to start production and are bred up to a commercial size (400–450 g). The average eFCR for the analysed year was 2.65.

2.3. Life cycle inventory

The data collected for each of the farms analysed in this study are shown in Table 1. Both primary and secondary data were used for the analysis. Primary data were collected directly from the analysed farms through questionnaires and interviews with the farm's specialist technicians. Specifically, primary data were retrieved for the quantity and size of juveniles seeded; FCR values with the amount of feed given and the percentage of individual ingredients were primary data (Supplementary materials, tables S1-S4). Primary information was also collected regarding the structure of the farms, with their respective infrastructure and equipment, as described in the previous section: for coastal farms, these data refer to the number of cages used for rearing, their composition in terms of materials, their distance from the coast, their size and the composition of the equipment fleet, including the useful life of all components included in the analysis; for land-based farms, these data refer to the number of tanks or ponds, the pumps required to ensure the required water flow, the filters, the anti-predator net including the useful life of all components included in the analysis; Energy consumption was extrapolated directly from the company's

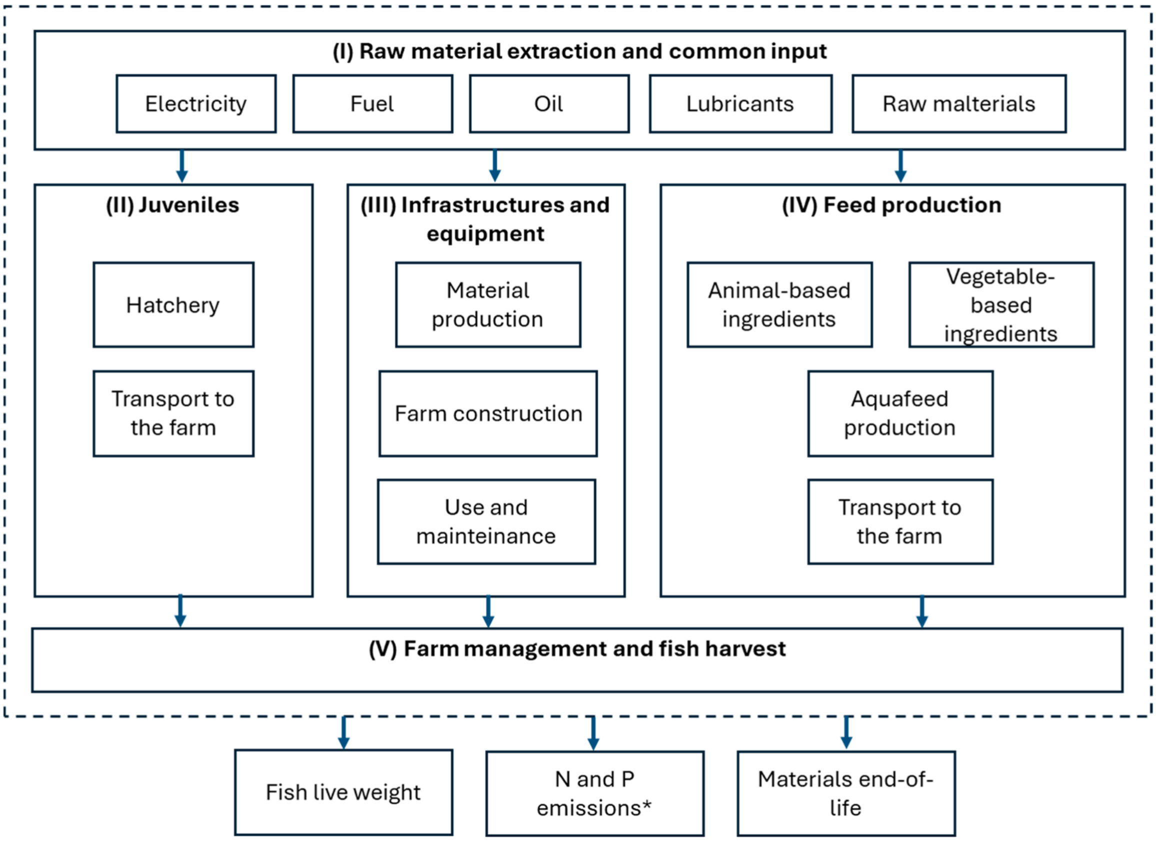

Fig. 1. Figurative representation of the system boundary of this study. *N and P emissions are part of the life cycle of fish production, however they have no impact on CED.

Table 1
Inventory analysis referring to the production year analysed for each farm.

Main parameters	LF1	LF2	CF1	CF2
Production biomass (tonnes)	456	455	1800	1340
Mortality rate (%)	20	6.8	14	5.7
Juveniles (tonnes)	5.5	3.8	10.4	22.6
Juveniles average mass (g)	3.5	5.25	2	4.7
Liquid oxygen consumption (kg)	968,000	2497,266	/	/
Feed (t)	1130	1191	3890	3506
Energy Inputs				
Electricity (kWh)	4328,726	1784,686	23,000	/
Fuel consumption (l)	14,600	6611	121,700	100,802
Gas consumption (m^3)	/	/	541	/
Infrastructures (total in the facility)				
Boats (#)	/	/	6	6
Fish cages (#)	/	/	32	44
Ponds (#)	50	63	/	/
Anti-predator net (m^2)	21,000	25,860	/	/

records and concerns the consumption of diesel for boats for coastal farms and the consumption of electricity for land-based farms.

Secondary data obtained from the Ecoinvent V3.9 database (Ecoinvent Centre, 2022) were used to model the impact of raw materials used and fuel production and procurement. For the modelling of individual feed ingredients, secondary data obtained from both the Ecoinvent and Agrybalyse (Koch and Salou, 2022) databases were used. In addition, energy consumption and the amount of water used for feed formulation were obtained from Nemecek et al. (2007). For the impact of electricity, data from the Ecoinvent database on the Italian national electricity mix were used. Finally, literature data from García et al. (2019) were used to model the impact of fingerling production.

2.4. Energy analysis

To characterize all inventory data in terms of their impact on Cumulative Energy Demand (CED), the method based on Ecoinvent version 1.01 and subsequently expanded by PRé for the energy resources available in the SimaPro database was applied (Frischknecht et al., 2007). In particular, the fuels' higher heating values default version of CED was used. The characterization factors of this method are divided into 5 sub-categories: (I) Non-renewable, fossil (NR-f); (II) Non-renewable, nuclear (NR-n); (III) Non-renewable, biomass (NR-b); (IV) Renewable, biomass (R-b); (V) Renewable, water (R-wa); (VI) Renewable, wind, solar, geothermal (R-wsg). The analysis was conducted using the SimaPro v9.5 software.

2.5. Results interpretation and scenario analysis

Contribution analysis was carried out to identify the energy demand of the individual sub-processes. In particular, the following sub-processes were taken into consideration: i) electricity consumption; ii) fuel consumption; (III) feed production and supply; (IV) liquid oxygen production and supply; (V) juveniles production and supply; (VI) infrastructure and equipment production, maintenance and disposal;

A scenario analysis with different energy sources was performed. In more details, for land-based farms, the current national electricity mix was replaced with the projected 2030 electricity mix, according to INECP, (2019) (Table 2). The Ecoinvent V3.9 database was used for modelling electricity derived from various sources.

Regarding coastal farms (CF1 and CF2), the consumption of traditional diesel has been completely replaced by the consumption of biofuel (B100), with a calorific value of 37.3 MJ/kg and a density of 890 kg/m^3 (EMEP/EEA, 2023). To model the impact of biofuel production, the Ecoinvent process for the production of Fatty-Acid-Methyl-Ester (FAME)

Table 2
Comparison between the percentage distribution of energy sources in the current national electricity mix (baseline, source Ecoinvent) and the scenario reported by INECP for 2030 (scenario 2030).

Source	% on total electricity mix	
	Baseline	Scenario 2030
Blast furnace gas	0.04	0.86
Oil and petroleum products	8.57	1.2
Natural gas	38.25	34.15
Renewables and biofuels	38.2	53.92
Hydro power	15.10	*14.6*
Wind power	6.43	*11.88*
Solar photovoltaic	10.38	*21.22*
Geothermal	1.99	*2.09*
Primary solid biofuels	/	*1.9*
Biogas	4.3	*1.71*
Renewable municipal waste	/	*0.51*
Non-renewable waste	1.75	0.51
Import net	13.19	8.46
CSP	/	0.89
Total	100	100

was considered.

3. Results

The results of the absolute impacts and the percentage of individual energy sources on the CED are reported in Table 3. The absolute results show a significant range in CED. Specifically, in the two LB farms, the CED is 168,535 and 188,642 MJ/t, while it is lower in the two coastal farms, with values of 66,224 and 76,507 MJ/t for CF1 and CF2, respectively. The percentage difference between the CED of LF2 (worst environmental case) and CF1 (best environmental case) is 65 %; the percentage difference between LF1 and LF2 is 11 %, while CF2 has a CED 13 % higher than CF1. These differences are primarily driven by both the eFCR and the CED per kg of feed. Specifically, in the two coastal farms, while CF2 shows an FCR approximately 23 % higher than CF1, the CED per kg of feed used in CF2 is about 30 % lower compared to the feed used in CF1, which compensates for the higher FCR and results in a lower overall increase in CED than expected.

LF2 is therefore the farm with the highest CED, due to a higher electricity consumption per ton of fish produced. In all subcategories, it has the highest impacts, except for the NR-n category (16,402 MJ/t), where LF1 has the highest impact (37,624 MJ/t). Although with the second largest CED, LF1 has the lowest impact in the NR-b (34 MJ/t) and R-b (22,434 MJ/t) categories. CF1 and CF2, on the other hand, have the lowest cumulative impacts as well as in all other impact categories. Additionally, CF1 consistently has lower impacts than CF2.

The NR-f category represents about 50 % of the CED in all analysed cases: specifically, it represents 53.4 % and 59.7 % of the CED in LF1 and LF2, and 57.4 % and 47 % in CF1 and CF2. In 3 out of the 4 cases, the second contributor to CED is R-b (20.5 % in LF2, 33.8 % in CF1, and 41.4 % in CF2), while in LF1 the second contributor is NR-n (22.3 % of the CED), followed by R-b (13.3 %). Overall, the energy demand from non-renewable sources is greater than that from renewable sources: specifically, in LF1 and LF2, the non-renewable categories represent 75.7 % and 68.5 % of the CED, respectively, while in CF1 and CF2 they represent 56.3 % and 43.7 % of the CED, respectively.

Fig. 2 shows the impact share related to each subprocess of the system for each category of energy source (as explained in Section 2.5). The main difference between the two rearing systems is the use of electricity and liquid oxygen in land-based systems. These two factors, in the NR-f category, together represent 56,216 MJ out of 89,956 MJ total in LF1, while in LF2 they account for 78,625 MJ out of 112,594 MJ total. The feed, on the other hand, represents 30,359 and 30,304 MJ, which is similar to those found in CF1 and CF2, respectively, at 31,558 and 31,099 MJ. In the NR-b category, feed in LF2 farm has a much greater impact (241 MJ/t) compared to the other farms (25, 49, and 90 MJ/t for LF1, CF1, and CF2, respectively). Oxygen consumption is the main contributor for the NR-n demand in LF1, accounting for 31,006 MJ out of a total of 37,624 MJ/t; on the contrary, energy consumption in this category impacts more in LF2 (8342 MJ) compared to LF1 (3441 MJ/t). In this category as well, the impact due to feed in the different systems is similar and ranges from 2712 MJ/t in LF1 to 6545 MJ/t in CF2. The R-b category is almost entirely due to feed consumption in all the analysed farms: in LF1 and CF1, the impact is similar (19,666 and 21,971 MJ/t, respectively), while it is also similar but higher between LF2 and CF2 (36,221 MJ and 31,474 MJ/t, respectively).

Significant differences between the two types of farms are also reported in the R-wa and R-wsg categories, where CF1 and CF2 have much lower impacts compared to LF1 and LF2. In detail, in R-wa, the impact of CF1 and CF2 is almost entirely due to feed (957 and 997 MJ out of a total of 1198 and 1134 MJ/t, respectively), while in LF1 and LF2, besides feed (927 and 883 MJ/t), the impact is mainly due to oxygen consumption (5611 and 1999 MJ/t) and electricity consumption (3478 and 8433 MJ/t). A similar trend is observed in the R-wsg category, where feed is responsible for 157 and 477 MJ/t out of a total of 330 and 582 MJ/t in CF1 and CF2; in LF1, the impact is divided between electricity

Table 3
Absolute impacts for each farm and percentage contribution to CED by category. Conditional formatting highlights the highest impacts in red, decreasing through yellow to green. Legend: NR-f (Non-renewable, fossil); NR-n (nuclear); NR-b (biomass); R-b (Renewable, biomass); R-wsg (wind, solar, geothermal); R-wa (water). UF: 1 t of fish.

Categories	LF1		LF2		CF1		CF2	
	Value (MJ)	% on CED	Value (MJ)	% on CED	Value (MJ)	% on CED	Value (MJ)	% on CED
Non-renewable, fossil	89,956	53.4	112,594	59.7	38,031	57.4	35,993	47.0
Non-renewable, nuclear	37,624	22.3	16,402	8.7	4,213	6.4	7,004	9.2
Non-renewable, biomass	34	0.02	257	0.1	67	0.1	99	0.1
Renewable, biomass	22,434	13.3	38,617	20.5	22,386	33.8	31,696	41.4
Renewable, water	8,334	6.0	9,432	6.0	330	1.8	582	1.5
Renewable, wind, solar, geotherm	10,153	4.9	11,340	5	1,198	0.5	1,134	0.8
CED	168,535		188,642		66,224		76,507	

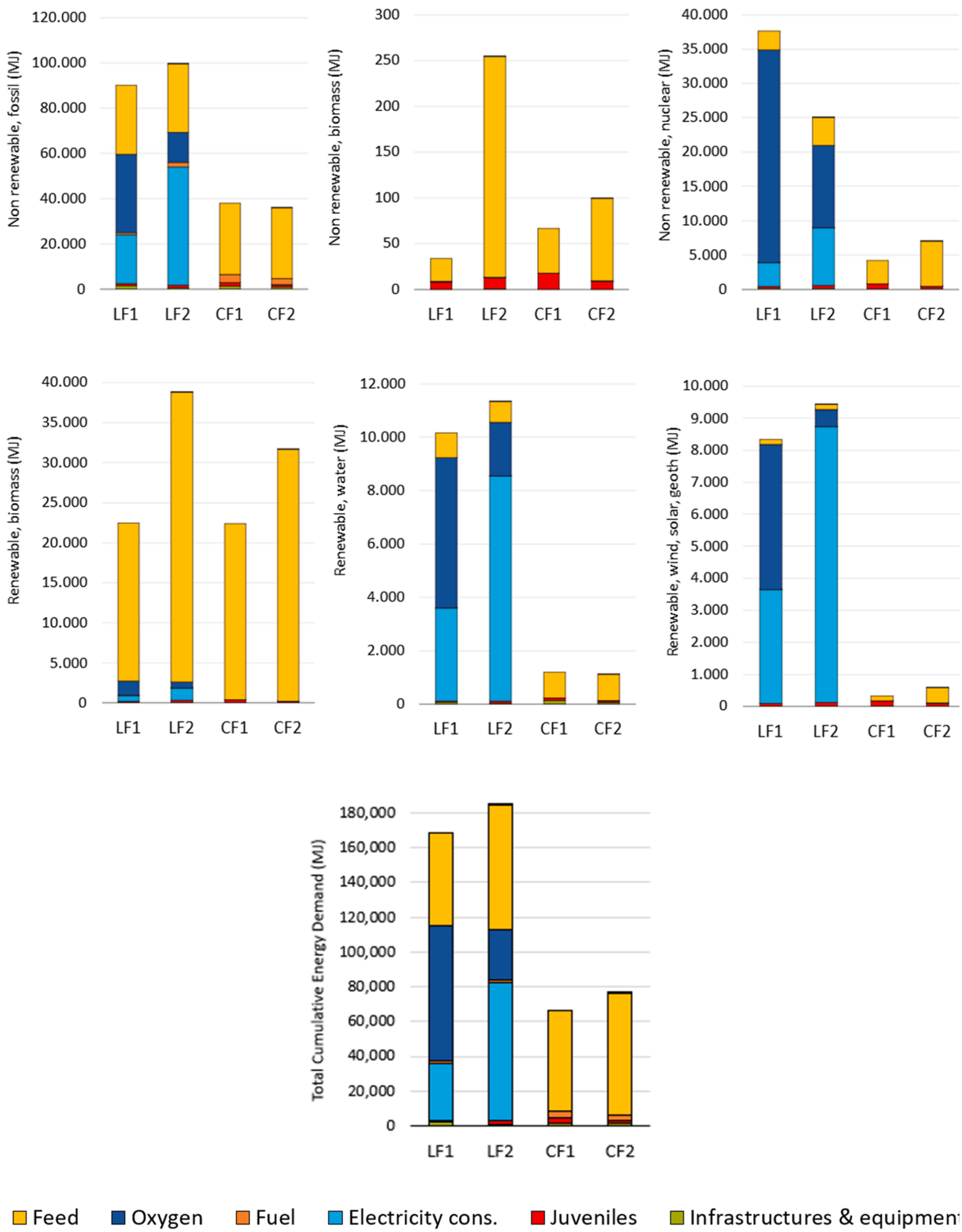

Fig. 2. Analysis of the contributions of absolute values for all analysed CED categories and the CED. UF: 1 t of fish.

consumption (3553 MJ/t) and oxygen (4541 MJ/t), while in LF2, the impact of electricity is higher (8615 MJ/t), but the impact of oxygen is lower (535 MJ/t).

Finally, in the characterization of CED, the feed has a similar impact in LF1 and CF1 (53,837 and 58,083 MJ/t, respectively) and is also similar but higher between LF2 and CF2 (71,784 and 70,682 MJ/t). It is also important to note that the total share of CED from the sum of electricity and oxygen is very similar between LF1 and LF2 (110,316 and 112,006 MJ/t), but in LF1, the predominant share is due to oxygen (77,665 MJ/t), while in LF2, it is due to electricity (79,163 MJ/t).

Lastly, other production factors (fuel, infrastructures and equipment, and juveniles) play a minor role in the definition on CED and other subcategories.

3.1. Scenario analysis implications

The relative variations between the real case scenarios (RS) and the alternative scenarios (AS) in all sub-categories and in CED are shown in Table 4.

For LF1 and LF2, the main variation concerns the increase in the use of renewable energy from wind, solar, and geothermal sources, with an increase in this category of 34 % in LF1 and 72 % in LF2. Additionally, renewable energy from water sources also increases by 1 % in LF1 and 2 % in LF2. Conversely, and as expected, non-renewable sources decrease: NR-f decreases by 2 % in LF1 and 5 % in LF2, NR-n decreases by 3 % in LF1 and 15 % in LF2, while NR-b remains constant.

For CF1 and CF2, the use of biodiesel significantly increases the NR-b category (+126 % in CF1 and +53 % in CF2), accompanied by a decrease in NR-f by −6 % in CF1 and −4 % in CF2. R-b also increases by 11 % in CF1 and 5 % in CF2. Finally, the other categories have more contained variations, ranging between 1 % and 2 % in both farms.

Finally, the different sources of energy supply, and therefore the different infrastructures and supply chains that characterize them, change the impacts of the subcategories but have practically no effect on the CED of the farms, with contained variations always below 1 %.

Regarding the characterization of CED, Fig. 3 shows the share of the energy from non-renewable and renewable sources in the two scenarios (RS and AS).

In all cases, in AS, renewable energy increases and is greater than in the RS, and consequently, non-renewable sources show an opposite trend. Specifically, in LF1, T-NR decreases from 76 % to 74 %, while T-R increases from 24 % to 26 %. In LF2, T-NR drops from 69 % of the total to 65 %, while T-R rises from 31 % to 35 %. The same trend is observed in coastal farms: in CF1, T-NR decreases from 64 % to 60 % of the total energy, while renewable energy increases from 36 % to 40 %. Finally, in CF2, T-NR decreases from 56 % to 54 %, while T-R increases from 44 % to 46 %. For further details on the absolute values of the various categories and their percentages of the total, refer to Table S5 in the Supplementary materials.

Table 4
Percentage changes in impacts of the alternative scenario (AS) relative to the real scenario (RS). AS energy requirements are based on assumptions in Section 2.5.

	Δ % (AS-RS)/RS			
Categories	**CF1**	**CF2**	**LF1**	**LF2**
Non-renewable, fossil	−6 %	−4 %	−5 %	−2 %
Non-renewable, nuclear	1 %	0 %	−15 %	−3 %
Non-renewable, biomass	126 %	53 %	0 %	0 %
Renewable, biomass	11 %	5 %	−2 %	−1 %
Renewable, water	2 %	1 %	72 %	34 %
Renewable, wind, solar, geotherm	2 %	1 %	2 %	1 %
Cumulative Energy Demand	0.35 %	0.19 %	−0.6 %	−0.3 %

4. Discussion

This study analysed and characterized the CED of different aquaculture farms across different sub-categories. As expected, land-based farms showed a higher CED compared to coastal farms. According to our knowledge, no study so far has specifically focused on the CED of ESB and GSB production in the Mediterranean, although there are reviews on energy use in aquaculture and some LCA studies on those species that also report this impact category. In more detail, the results of this study are in line with those of other LCA studies focusing on ESB and GSB production. In particular, Abdou et al. (2017) report a CED of 57,198 and 51,098 MJ/t for ESB and GSB, respectively, farmed in a coastal sea-cage farm. Two other LCA studies (Abdou et al., 2018 and Garcia Garcia et al., 2016) reported CED values of ESB and GSB production: Abdou et al., (2018) reported a CED ranging from 44,000 to 59, 000 MJ/t, while Garcia Garcia et al., (2016) reported a higher value (98, 120 MJ/t). The only LCA study in the literature focused on land-based farm is Jerbi et al. (2012): they reported a much higher CED than the previous studies, due to the high energy consumption required, with values of 280,000 MJ/t and 175,000 MJ/t, which are, in any case, in the same order of magnitude as LF1 and LF2 of this study (Fig. 4). The energy demand for land-based systems can be highly variable. With an energy demand of 9.5 and 5.3 kWh/kg (i.e. 34,200 and 19,080 MJ/t) of fish, respectively, the LF1 and LF2 farms in this study rank low compared to RAS systems (3–81.46 kWh/kg of fish, Ayuso-Virgili et al. 2023, i.e. 10,800–293,256 MJ/t of fish), but have a higher energy demand when compared to other Flow Through Systems (FTS), where Samuel-Fitwi et al. (2013) reports an energy demand of 2.55 kWh/kg of fish (equal to 9180 MJ/t).

More generally, Pelletier et al. (2011) analysed the energy intensity of agriculture and food systems, including aquaculture; they reported an energy demand for aquaculture systems ranging from 20,000 MJ/t (for farmed Tilapia) to 50,000 MJ/t (for farmed ESB) of product. Additionally, the average energy demand for fisheries was reported to be about 35,000 MJ/t of fish. However, these latter results concerning fishing activities are highly variable due to the significant differences between artisanal fleets, which rely on wind, tides, and manual labour, and highly industrialised vessels equipped with advanced technologies. According to Troell et al. (2004) energy inputs could be divided into direct and indirect (or embodied) energy: direct energy inputs to aquaculture operations encompass a range of activities, including the collection/-production of juveniles, general system operations, and the harvesting; indirect (or embodied) energy is represented by fixed capital inputs such as different forms of enclosures (tanks, nets, etc.), feeders, aerators, pumps, boats, vehicles, etc. As reported by Tyedmers (2004), unlike other food production sectors, direct inputs account for the preponderant share (75–90 %) of energy demand in industrial fishing activities. In aquaculture systems, the ratio between direct and indirect energy can vary greatly depending on the type of system. While open systems rely on ecosystem services to maintain water quality and, in some cases, natural productivity, closed systems must be supplemented with increasing levels of material and energy inputs (Pelletier et al., 2011). Intensive land-based flow or recirculating systems are often characterised by significant energy input for activities such as pumping and filtering water (Badiola et al., 2018). In land-based systems, the direct consumption of electricity for water supply and pumping, and the operation of aerators represents a significant share of the CED. For example, in LF1 and LF2 of this study, the direct electricity consumption represents 19 % and 42 % of the CED, respectively. In coastal farms, on the other hand, the direct energy consumption is much lower, as it is mainly represented by the fuel consumption for navigation to reach the sea-cages, while the predominant share of energy is due to the use of aquafeeds. For instance, in CF1 and CF2 of this study, the share of CED linked to fuel consumption is 5 %, while that linked to feed reaches up to

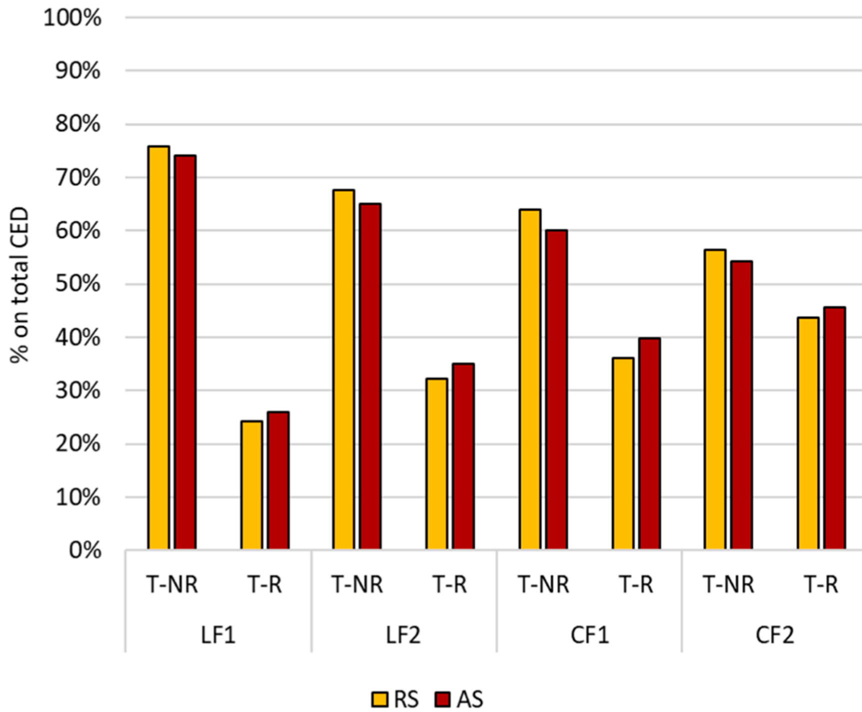

Fig. 3. Comparison of the percentages of total non-renewable energy (T-NR) and renewable energy (T-R) on the CED of the real scenario (RS) with the alternative scenario (AS).

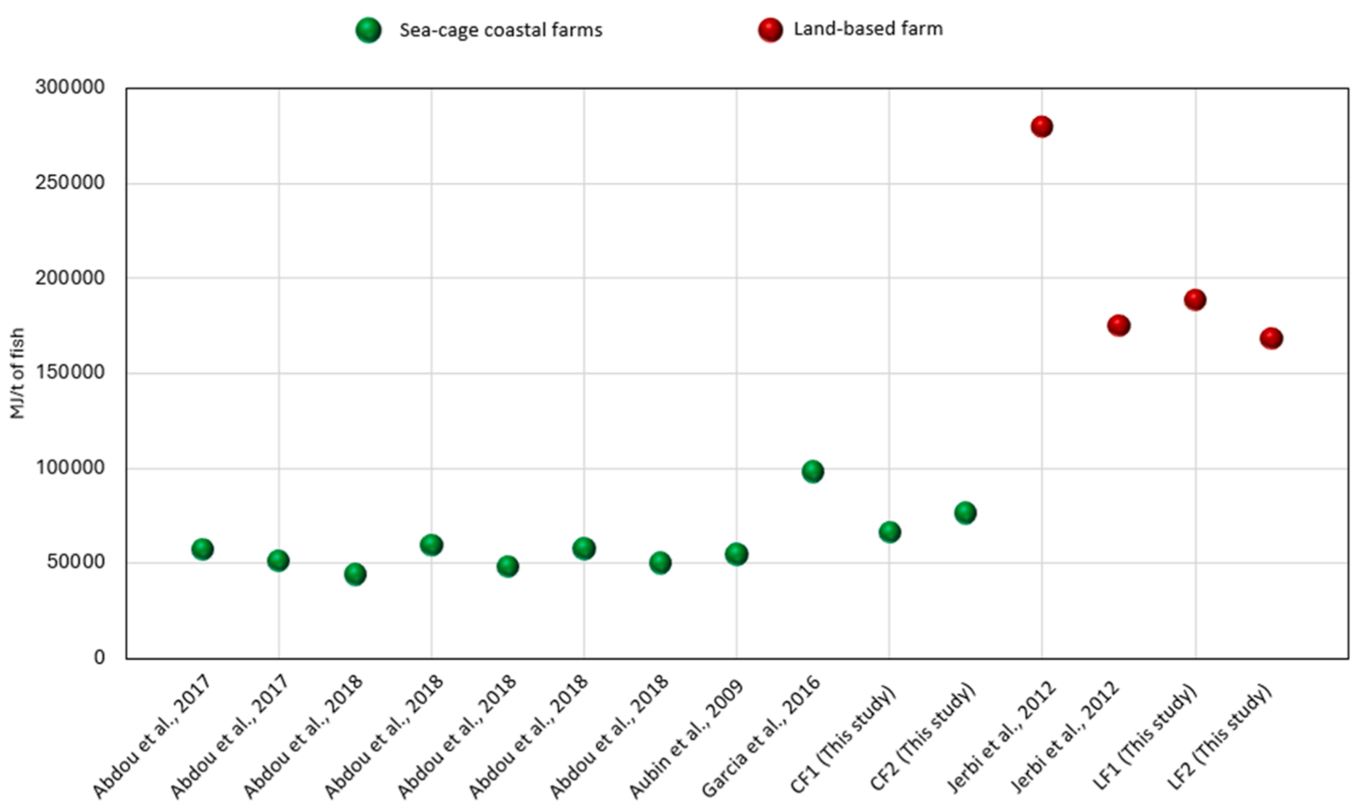

Fig. 4. Comparison of CED values with values reported in LCA literature papers for Seabass and Seabream.

90 %. The same trend can also be found in Abdou et al. (2017) where feed represented 72 % and 79 % of the total, while fuel consumption accounted for 8 % and 7 % of the CED. This is also confirmed in other species: for example, Pelletier et al. (2009) reported that aquafeed is responsible for over 90 % of the CED in globally produced Atlantic salmon farming. Therefore, feed composition also plays a key role in determining the CED of aquaculture systems, as very different energy requirements can be incorporated into different feed sources

(Henriksson et al., 2013).

The low share related to fuel is certainly due to excellent farm management and the large scale of the farm, where the fuel is distributed over a large quantity of farmed fish. The fuel intensity of CF1 and CF2 is indeed 68 and 83 l/t of fish, respectively. Parker et al. (2018) reported a global average fuel intensity of 489 l/t of fish for fisheries, which also explains the difference between direct and indirect energy in fishing and aquaculture. Beyond fuel consumption, a potential mitigation strategy for reducing total energy demand, as studied by Rossi et al. (2024), is the use of recycled copper alloys for sea cage nets. This solution offers a viable alternative to traditional materials, as copper-based nets have a longer lifespan, require less maintenance, and provide natural antifouling properties, which help reduce the environmental burden associated with net cleaning and replacement. Rossi et al. (2024) reported a 13 % reduction in CED when using nets made from 100 % recycled copper. However, they also highlighted that if the source of the alternative material is not recycled, the results could be entirely reversed, leading to a significantly higher environmental impact.

The use of energy from fossil and non-renewable sources has already peaked, and several forecasts indicate that the use of renewable sources is set to grow significantly, potentially covering 30–80 % of energy needs by 2100 (Monforti-Ferrario et al., 2015). Currently, hydropower and traditional biomass account for a significant part of the global energy mix, contributing about 18 % of global energy consumption. On the other hand, new renewable sources, such as solar, wind and geothermal energy, account for only about 2 % of global primary energy consumption. In this context, in order to address problems such as global warming, it will be crucial to integrate local energy sources into national or regional systems, using the most appropriate energy, whether local or imported (Fridleifsson, 2001). Therefore, it is important for industry to support energy savings at the farm level (Rosen and Dincer, 2001) and the replacement of fossil fuels with renewable sources (Aubin et al., 2009).

A scenario analysis with different energy sources was conducted in this study. The scenarios created in this study allow for an increase in the share of renewable energy used in the farms analysed: note that these are hypothetical scenarios, no modifications to the plants and farms have been considered and results in reality may vary. In any case, increasing renewable sources, as already highlighted in other studies (Badiola et al., 2018) can also decrease the environmental impact in terms of climate change of the aquaculture sector. In this study, the electricity of the alternative scenario has an environmental impact on climate change, per kWh, that is 15 % lower than the current Italian national electricity mix (0.322 kg CF2 eq/kWh for the former, 0.382 kg CF2 eq/kWh for the latter), while the use and combustion of biodiesel has an impact on climate change of 11 % less than a conventional diesel (0.083 kg CF2 eq/MJ for the former, 0.094 kg CF2 eq/MJ for the latter). Finally, it is important to remark that alternative scenarios are simulations based on assumptions and average values from the literature, therefore, the reality may differ; This is particularly true for land-based farms, where the environmental impacts can vary significantly depending on the country, as energy sources are highly site-specific and differ in type and proportion. This also introduces the topic of the upscalability of the achieved results.: The potential for upscaling the results depends primarily on the farming system and species considered. For land-based systems, while the CED may remain constant, the share of renewable energy increases significantly in regions with a higher penetration of renewables compared to those relying predominantly on fossil fuels, leading to a different environmental profile. Coastal farms are less influenced by local energy variability, making their performance more consistent and potentially scalable across different regions. Sea bass and sea bream farming are well-standardized practices, which ensures that upscaling within these species is feasible and reliable. However, particular attention is needed when extending the approach to other species, due to differences in FCR, growth cycles, and specific environmental requirements. These variations can significantly affect energy consumption and environmental performance.

5. Conclusions

This study provides a detailed analysis of the CED associated with ESB and GSB production in different aquaculture systems in the Mediterranean region. By comparing land-based farms and coastal sea-cage farms, the research highlights significant differences in energy consumption patterns and identifies key areas where energy efficiency improvements can be made. The results demonstrate that land-based farms have a significantly higher CED compared to coastal farms, primarily due to the extensive use of electricity for water circulation, aeration, and temperature control. In contrast, coastal farms, while less energy-intensive, still exhibit substantial energy demands, particularly from the production and use of aquafeeds. These findings align with previous studies, confirming that the type of farming system plays a critical role in determining the overall energy footprint of aquaculture operations.The scenario analysis suggests that increasing the share of renewable energy could significantly reduce the environmental impact of land-based systems by 2030. However, the actual implementation of such strategies would require site-specific considerations, depending on local energy infrastructure and availability. In conclusion, this study highlights that optimizing energy use in aquaculture is crucial for improving sustainability and reducing environmental impacts. While coastal systems appear more energy-efficient, targeted strategies are essential to improve energy management in both land-based and coastal farms. As global demand for seafood continues to rise, integrating renewable energy and promoting energy-efficient technologies will be key to ensuring the long-term sustainability and economic viability of aquaculture.

CRediT authorship contribution statement

Bacenetti Jacopo: Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization. **Zoli Michele:** Writing – review & editing, Writing – original draft, Software, Methodology, Investigation, Data curation, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.aquaeng.2025.102525.

Data availability

Data will be made available on request.

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