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Design and Simulation of a Floating Solar Photovoltaic System for an Offshore Aquaculture Site in Canada

Nadeem Asgher[1*], Tariq Iqbal[2]

[1, 2] Department of Electrical Engineering, Faculty of Engineering and Applied Science, Memorial University of Newfoundland, St. John's, Canada
E-mail: mnasgher@mun.ca

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Abstract— This article presents the design and commercial feasibility of a floating solar photovoltaic (FSPV) power system for an offshore fish farm site located in the Newfoundland province of Canada. The offshore fish farms are energy-intensive units, and the fish feeding system is the primary energy consumer. Due to the remote location, the grid/utility power infrastructure does not exist, and diesel generators fulfill energy needs, which is expensive and detrimental to the environment. A FSPV power system is proposed as a replacement for the fossil fuel energy source. A comprehensive study is conducted to investigate the actual energy requirements of a site and an appropriate hybrid solar system is designed using Homer Pro software. The designed system's techno-commercial feasibility is evaluated based on three different scenarios (base, ideal and worst). The obtained results show that the renewable energy penetration for all cases is very convincing and encouraging. The Levelized Cost of Energy (LCOE) computed by the software for all three cases is compared with the existing setup produced energy cost. It reveals that the designed FSPV produces significantly economical power. Overall, the outcomes of this investigation demonstrate the potential of FSPV systems as a viable and sustainable solution for powering fish farms and contributing to the sustainability of the aquaculture industry.

Keywords— Aquaculture; Floating solar PV power system; HOMER Pro; Levelized cost of energy; Canada.

1. INTRODUCTION

According to the report of the State of World Fisheries and Aquaculture 2022 by Food and Agriculture Organization (FAO) of United Nations, the world saw the historic production of 178 million tons of aquatic animals in the year 2020. The total production is a combination of marine and inland fish farming, contributing 63% and 37% percent, respectively [1]. The estimated value of the said production is around USD 406 Billion. The direct human consumption share in total production is dominant at 89% and the remaining 11% is used in making fish oil etc. A positive trend in human consumption of aquatic animals is seen in the last around six decades which grew at an average annual rate of 3% from 1961 to 2019, more than the global population growth rate. Furthermore, the average global per capita consumption trend of aquatic foods over the last years has significantly increased, in 1961 it was 9 kg whereas it has reached 20.2 kg in 2020 [1]. The rise in per capita consumption is influenced by income growth, inclined consumer behavior towards healthy eating, better supply/distribution network, and the introduction of better technology.

Food security is a growing challenge for the world. It will become a dilemma in the coming years because global warming and resultant natural disasters threaten world food

* Corresponding author
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production resources. Therefore, the world must find ways to produce sustainable food. 70% of the earth's surface is covered with water which provides a clear viability for aquatic animals to be served as food to the rising population.

Fish are bred, raised, and harvested as part of fish farming, which is also known as aquaculture, in a setting that closely resembles their natural habitat. In a fish farm, fish production and growth are maximized/optimized by providing the right feed, maintaining water quality, and doing routine health checks on the fish. Fish farms can be developed over the oceans, rivers, lakes, or ponds. There are a variety of prevalent techniques of fish farming in different parts of the world. North America and Europe mostly have net pens where the cage is fastened to the ground in the ocean, mostly close to the coastal area.

Seawater fish farming is also called offshore aquaculture, the fish is raised in a specialized and purpose-based designed enclosure (normally a cage) in the seawater. The most practical and well-liked method of offshore fish farming is open-cage aquaculture, which is being used for many years. The complete system comprises of flexible but floating collars, weights tied to the bottom surface, a net, and an anchorage system connected to the seabed [2]. The popular species of seawater are Salmon, Cobia, and Tuna. The typical system comprises the cage, the feeding mechanism, and the energy network. A balanced diet having a suitable proportion of protein, vitamins, carbohydrates, and fats is supplied through the feed lines. The mixture of diet is dependent on the farmed species. A large boat/ship called a feed barge holding the complete infrastructure comprising of power supply, feed, automated monitoring system, and crew is stationed near the cluster of net pen sites. The feed is stored in the silos which are placed on the feed barge and supplied to each cage with the help of feed blowers. The offshore fish farms provide relatively better water quality and hence yield healthy fish [3]. The power supply is arranged by diesel generators because of the non-availability of the grid/transmission network at the offshore location. The power requirement is usually high because of the automated fish feeders, freezers, air compressors, lighting, and the devices used by the deployed crew [4].

The idea of using renewable energy to meet the energy needs of the aquaculture industry can make it a more reliable approach toward global warming concerns and will be a breakthrough in improving the sustainability of the industry, as well.

Photovoltaic (PV) systems are one of the most widely used forms of renewable energy. Since it is renewable, infinite, and non-polluting, it is a desirable energy source compared to conventional fossil fuels like coal, oil, and gas. Installing solar photovoltaic systems over water bodies utilizing floating technology is a novel concept. The aquatic environment benefits from the floating solar installation since the solar plant's shadowing reduces algae growth, avoids excessive water evaporation, and it even improves the water quality.

1.1 Literature Review

The world population has recently hit a new peak and according to United Nations World Population Prospects Report 2022, the earth has seen 8 billion people in November 2022 which is expected to climb all-time high of 9 billion by 2050. The continuously rising population demands more food sources and fish can be an excellent source to overcome the global food security challenges. Furthermore, fish is also a richly nutritious food with abundant protein, fatty acids, minerals, and vitamins. Wild fish hunting is causing a considerable decline in the sea and rivers and is not sufficient to meet the seafood consumption rate and that's the primary reason behind increasing fish farming activities [5]. Aquaculture activities are broadly classified into land-based (freshwater) and offshore (seawater) fish farms. The offshore aquaculture system widely uses flexible floating cages to accommodate and raise fish. The said type of cage has a proven reputation for handling adverse weather conditions of the sea. The cages are normally located at least 300 m from the seashore. Robust mooring mechanisms are used to secure the cages in place. Chains, ropes, and buoys are used in these systems to keep the cages anchored in the water and from drifting away. The feed that has been specially prepared to fulfill the nutritional needs of the species being grown is typically used for feeding. The use of automated feeding devices can provide controlled and regular feeding. The feeding is done through the automated machines which are placed on the floating ship, the feed is provided through pipes in the form of homogeneous pellets. The Dissolved Oxygen level (DO) is maintained in the cage with the help of air compressors. The DO content in water plays a pivotal role in fish survival, if it is less than 4 mg/L in the water, then the fish cannot breathe and eventually dies. The optimum level of DO in the water for better fish growth is 9 mg/L [5]. The DO level in the water is artificially maintained/increased with the help of aerators (usually electric motors or air compressors).

The offshore fish farms' operations rely heavily on electricity, feeding machines, air compressors, lighting arrangement for the cages, sensors, refrigeration, and instrumentation for monitoring are the primary energy consumers [6]. Further, the facilities developed for the operational staff also require electricity for lighting and heating, etc. These fish farms are not connected to the utility grid due to their remote location and rely on diesel generators for supplying electricity that runs 24/7.

Energy is used in maritime fish farms in two forms i.e., fuel (for transportation) and electricity. There is very limited research available on the energy assessment of offshore aquaculture in the form of electricity. However, the cumulative energy consumption (fuel used for transportation activities and generator operation) is given in [6]. A study conducted on a coastal fish farm in Norway states that electricity required for carrying out the growth-phase activities is around 700 kWh/day with a peak load of 100-120 kW during the feed time [7]. The feeding mechanism is one of the most electricity-consuming units with a share of 50% of the daily required electricity [7]. Another research states that the feeding machine/blowers are the leading and intensive power consumers which are placed on the deck of the feeding barge [8]. The automation trend in offshore aquaculture is increasing and companies are putting in more and more infrastructure to automate the fish feeding and remote monitoring system. Autonomous feeding systems have many advantages but have significant energy needs as well [9].

Solar energy is one of the most feasible and convenient renewable energy options that can bring sustainability and meet the energy demands of the aquaculture industry. According to [10], in a few hours at noon in bright sunlight and clear skies, solar radiation generates roughly 1000 W/m^2. The potential of solar power for aquaculture is very convincing.

The traces of solar power running the operations of inland fish farms are very vibrant. However, we cannot find any evidence of solar power installation for offshore aquaculture. Some of the literature found on utilizing solar power for inland fish farms is described below.

An off-grid solar power system of 1.1 kW is designed for a fish farm in Turkey to supply the energy and its performance is evaluated using HOMER software [11]. The aeration system is one of the most significant energy-consuming units in inland fish farms and a solar power system is designed to run the system for a large fish farm [12]. Another study considered the floating PV panels to power up the complete operation of a shrimp farm in Taiwan where the PV system designing is done on Helioscope. The proposed system can generate 32 MWh/month by installing 896 PV panels [13].

There are many types of solar systems i.e., rooftop, land-based, offshore, and floating. When compared to solar panels that are installed on land, floating solar photovoltaic panels (FSPV) provide several benefits, such as fewer obstructions that block sunlight, convenience, energy efficiency, and improved power generation efficiency because of the lower temperature under the panels. FSPV systems are similar to other kinds of PV systems. The only difference is that PV panels float on the water, the panels are anchored with the land but suspended on floats. The FSPV can be constructed on dams, lakes, and even oceans. The FSPV shall be a step forward in bringing sustainability to the aquaculture industry. According to the World Bank report [14], there is an enormous potential of generating around 400 GW (gigawatts) from FSPV around the globe. So, the potential is very well reckoned. Many countries working to harness the potential of FSPV systems and China is leading the ladder followed by Japan.

Due to this dependence on temperature, solar PV systems built on the surface of water benefit from significantly lower ambient temperatures due to the cooling action of water [15]. On average, efficiency of floating-type solar panels is 11% higher compared to ground-installed solar panels [16]. This technology has the potential to significantly reduce the cost of land and the cost of producing electricity.

Significant research has been done on setting up solar power plants for land-based fish farms. In this article, a novel concept is implemented where the floating solar PV panels are installed over an offshore fish farm water surface and all the operational energy needs of the fish farm are supplied by the Off-Grid solar power.

2. PROJECT SITE PARTICULARS

2.1. Site Description

The site is located near Red Island, Placentia Bay, North of the Atlantic Ocean, Newfoundland, province of Canada which has a historic association with the fish. Newfoundland is considered to be one of the best places for fishing in the world because of the gulf stream's warm waters and the chilly Labrador Current joint here. Nutrients are lifted to the top due to the mixing of these waters and the ocean floor's structure. The said phenomenon makes this place rich and sustainable for the fishing and seafood industry. The selected site is in the Atlantic Ocean, around 2 km from the land. It has a total of eight cages, seven have fish and one is kept spare. The circumference of each cage is 160 m, diameter of 50.95 m. Each cage accommodates 160,000 Salmon fish. There is one feed barge, two cages are on one side of the feed barge whilst the other six are on the opposite side, the said orientation can be seen in Fig. 1.

Fig. 1. Project site (offshore fish farm).

2.2. Load Profile/ Energy Demand

The primary load of the offshore fish farm is the fish feeding system. The feed is stored in the form of homogenous pellets in eight silos and is supplied to each cage with the help of three feed blowers, the rated power of the feed blowers is 30 kW, 22 kW and 22 kW. The operational hours of the feed blowers depend on the season and size of the fish. The Salmon growth rate in summer is high as compared to winter as the seawater temperature has a deep correlation with the growth of Salmon [17]. In summer, three meals are served in a day typically, breakfast, lunch, and dinner. Therefore, longer operational hours of the fish feeding system (8-10 hours) are observed in summer, posing high average electricity demand per day. During winter only lunch is provided, and fish remains in hibernation mode usually. The feed blowers run for 4-6 hours a day which means lower average electricity demand per day. On average, feed blowers run at 70% of their rated power.

There is one air compressor of 30 kW to collect the waste/dead fish from the cage and supply the oxygen, in case of need. The usual operation of the air compressor is 3-4 hours a day. Since the feed barge houses all the equipment, it is a multistory (3 floors) ship, and the lighting load is significant there. The indoor LED lights are 12 W each and 60 Nos whilst the outdoor area has 20 Nos, 100 W LED lights. The dissolved oxygen and salinity sensors are placed in each cage which are powered uninterruptedly. The cameras are also installed at each cage to monitor the health and activities of fish. There is a centralized control room where the input of all the sensors is received, and fish feed operation is also monitored. The control room is equipped with multiple power sockets, computers, lights, and automation equipment. All the load of equipment placed in the control room and other loads experienced by the staff (fridge, oven, TV, etc.) is combined as auxiliary load.

Table 1 shows the energy consumption of a typical day for June, the highest consumption month, the average energy demand per day is 721.7 kWh and the peak power is 79 kW. During the winter season, the temperature drops from -10 °C to -15 °C at the site, and the heating load is also added to the list. Further to this, the duration of the outdoor lights is also increased to 15 hours. Since the primary load (feeding system) is laid off relatively in winter, the accumulative demand remains lower than in summer. The energy demand in a typical day of winter is 575 kWh and the peak load is 82 kW.

Table 1. Load profile.

Load	Rated Power [kW]	Average Power [kW]	Operational Time [Hrs]	Consumed Power [kWh/day]
Feed Blower-1	30	21	10	210
Feed Blower-2	22	15.4	10	154
Feed Blower-3	22	15.4	10	154
Air Compressor (Aeration & Mud Collect)	30	21	4	84
Indoor LED Lights: (60Nos)	0.72	0.72	24	17.28
Outdoor LED Lights: (20Nos)	2	2	9	18
DO Sensors (8Nos)	0.008	0.008	24	0.192
Salinity Sensors (8Nos)	0.008	0.008	24	0.192
Fridge	0.8	0.8	24	19.2
Microwave Oven	0.9	0.9	0.5	0.45
LED TV (2 Nos)	0.17	0.17	8	1.36
Electrical Crane	50 kW	10	1.5	15
Control and Automation Equipment	3 kW	2	24	48
Total	110.2	79	115	721.7

The Single Line Diagram (SLD) of the existing electricity network at the project site can be seen in Fig. 2.

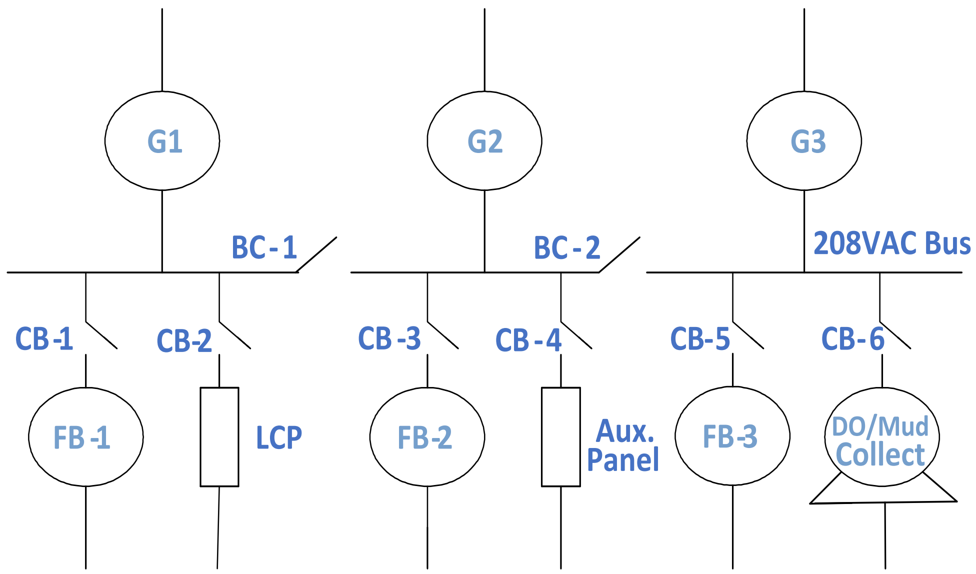


Fig. 2. SLD of the existing system.

2.3. Solar Resource

The determination of solar resources is the most fundamental step while designing the solar system for a particular site and it also helps to verify the techno-commercial feasibility of the project. The Homer Pro software provides reliable calculation while computing the monthly Global Horizontal Irradiance (GHI) based on the average of 22-year data taken from NASA meteorology. The GHI is a measure of the total radiations received by the ground, it is the summation of two components i.e. Direct Normal Irradiance (DNI) and Diffuse Horizontal Irradiance (DHI). The solar irradiation that comes directly from the sun in a straight line to the surface is termed DNI whilst the irradiation that doesn't follow the direct path and is dispersed in the environment and received from all directions is called DHI.

It can be seen in Fig. 3 that the highest solar resource is available in June (5.1 kWh/m^2/day) followed by May and July. Whereas the annual average available GHI is 3 kWh/m^2/day.

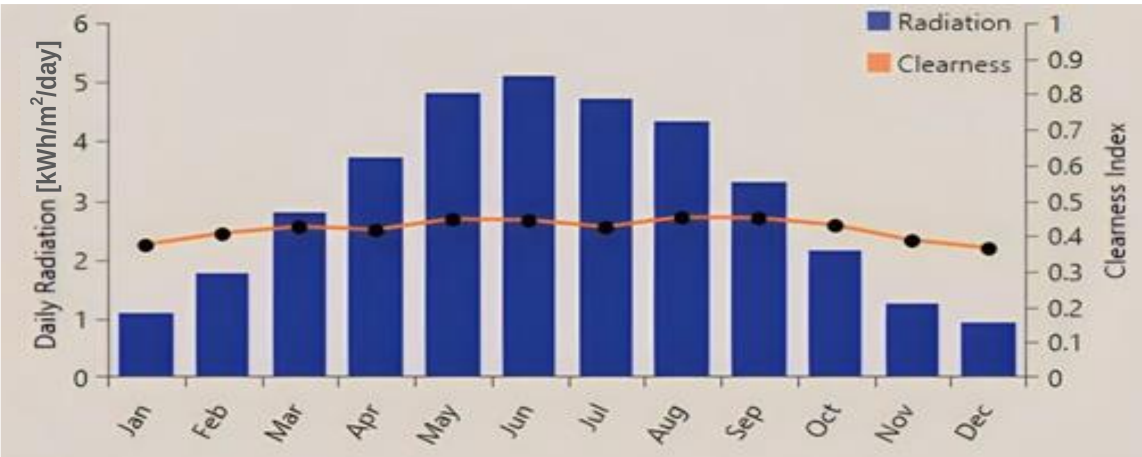


Fig. 3. Solar resource at the site.

3. SYSTEM DESIGN

The design of the Floating Solar PV system for the fish farm is done using the Homer Pro tool developed by the National Renewable Energy Laboratory (NREL) in the United States [18]. HOMER stands for Hybrid Optimization of Multiple Energy Resources. It is a software application used to design and analyze a power system's technical and financial aspects for stand-alone, remote, and distributed generation applications. HOMER Pro is simple to use, detailed, and takes in all the necessary variables when analyzing a power system.

The load profile determined above for the summer and winter months is given as input to the said tool. The hourly load is distributed based on the information collected from the site and the annual average load per day is computed as 651.15 kWh/day. There are two buses i.e. AC and DC. AC bus operates at 208 V whilst DC bus voltage is 360 V. The load and diesel generator are directly connected to the AC bus whereas PV panels and battery bank is connected to the DC bus as shown in Fig. 4.

Two different sensitivity variables are introduced to determine the techno-commercial feasibility of the designed system. The variation (10%) in solar resource and annual average per day load is assumed, and three different cases ideal, base and worst case are developed.

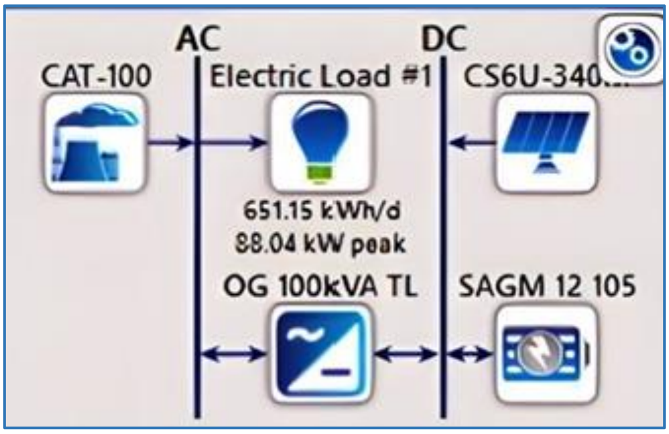


Fig. 4. Schematic of the designed system.

3.1. Component Selection

The PV panels of Canadian Solar, model CS6U-340M, a tier 1 and one of the most reputed PV panel manufacturers, are selected. The selected PV modules have 25 years performance warranty. Solar SAGM 12 105 models of the battery is chosen. The battery is manufactured by Trojan, USA, and enjoys distinguished reliability of performance. SOCOMEC-made inverter having model name SUNSYS PCS² OG 100 kVA TL has opted. 100 kVA Diesel Generator made by Caterpillar is considered.

3.2. Base Case

The base case is the actual prevailing scenario at the project site which is based on the following two fundamental inputs.

The annual average per day solar resource is 3.00 kWh/m²/day and the annual average per day load is 651.5 kWh/day.

Homer Optimizer tool computed the best possible solution for the above-said inputs and recommended a solar PV power plant of 366 kW, 1077 modules each of 340 W. The monthly electricity production, referred to in Fig. 5, is a clear indication that solar production is largely dominant and fulfilling the load requirement comfortably with a share of more than 88%. Considering the financial and environmental challenges associated with diesel generators, it is kept as low priority source and to cope with the non-availability of solar energy, a sizeable battery bank of 542.1 kWh is designed. The said battery bank consists of 390 batteries and can serve the critical load of the fish farm for one whole day. There are 13 strings and each string has 30 batteries with a nominal capacity of 1.39 kWh. The configuration of the complete system is shown in Fig. 6.

The renewable penetration at every time step is calculated by Homer Pro using the following formulae (referred to as Eq. (1)). It indicates the proportion of the total produced energy from renewable energy resources.

$$Renewable\ penetration = \frac{P_{ren}}{L_{served}} \quad (1)$$

Pren is the energy generated by renewable energy resources and Lserved is the load served at a particular time step. The renewable penetration is found to be at 82.1% which depicts a very convincing and encouraging solution for the project site.

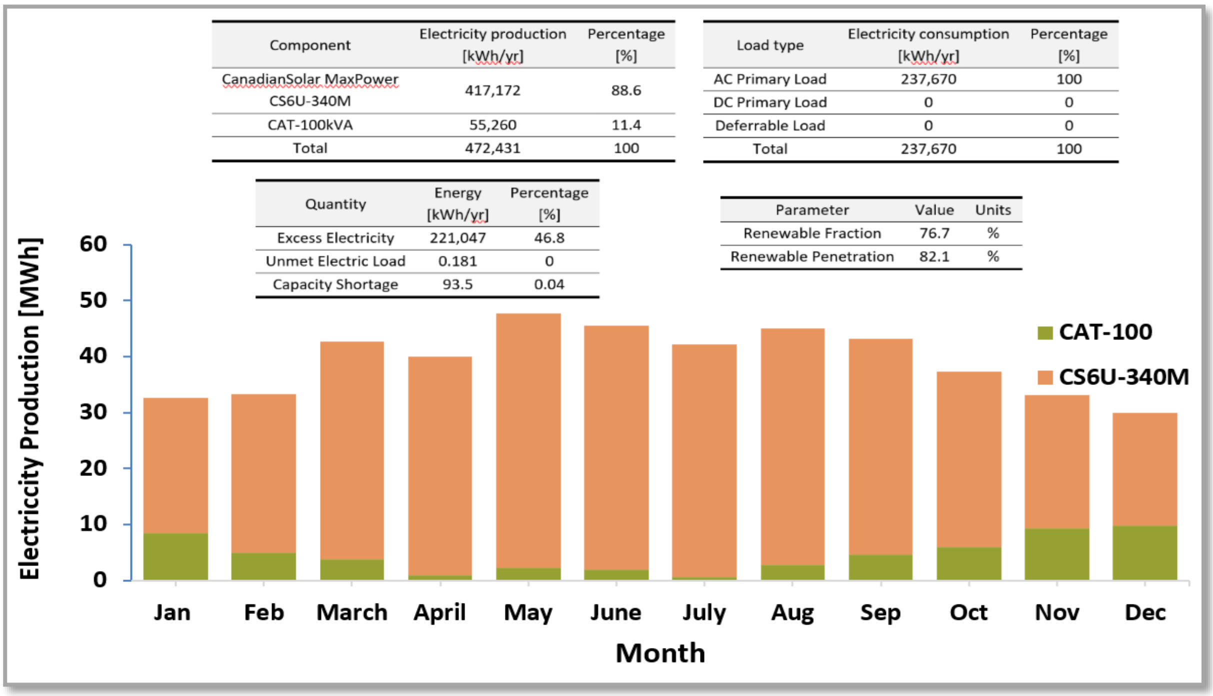


Fig. 5. Monthly electricity production by PV and generator.

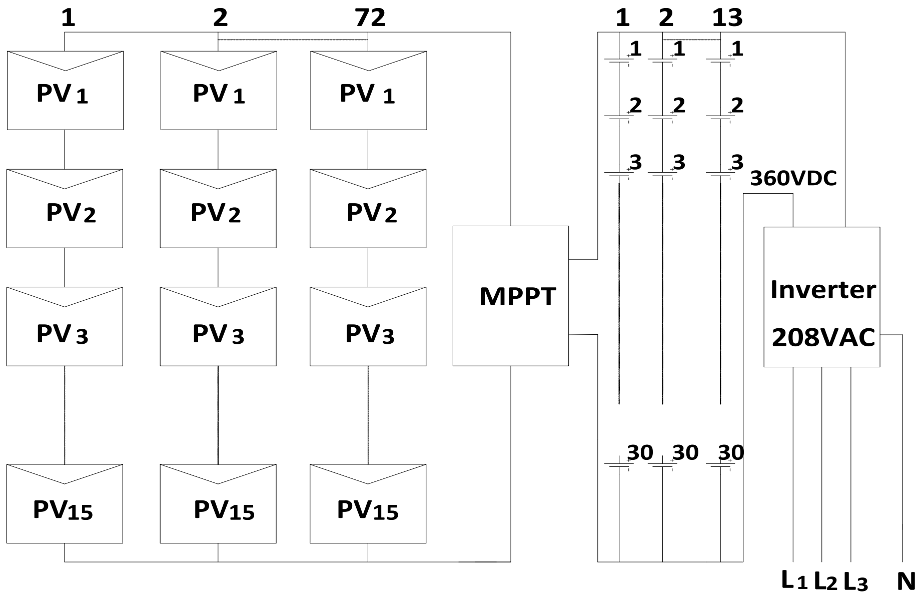
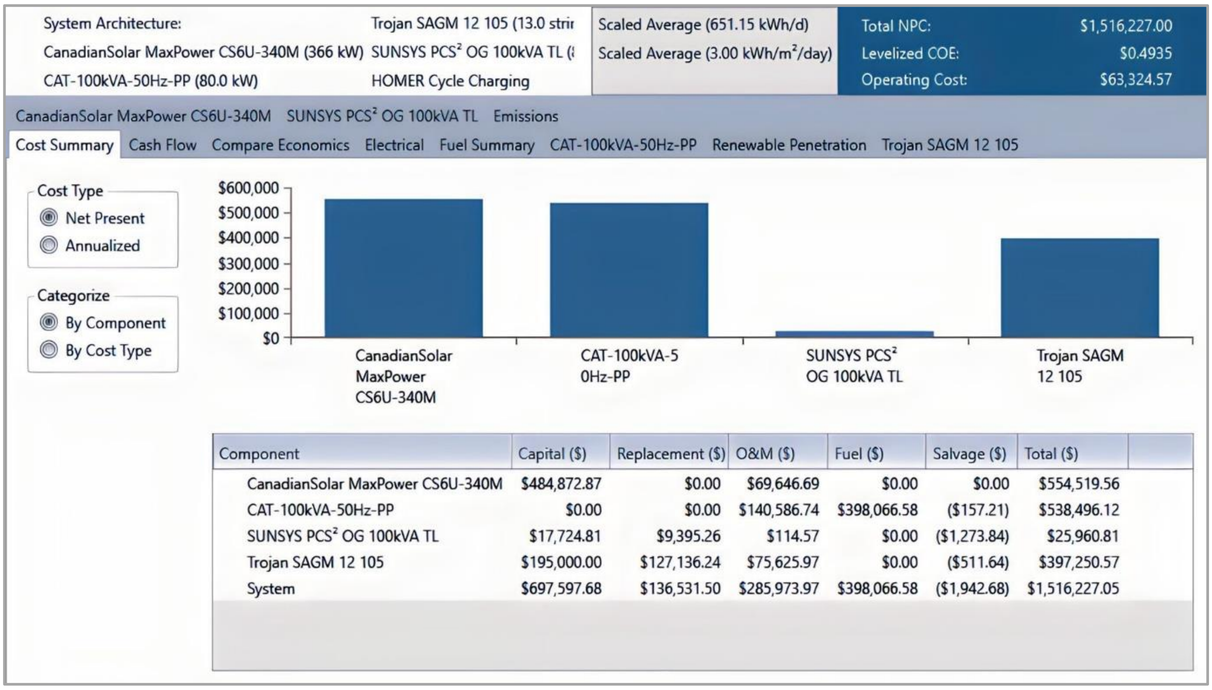


Fig. 6. Configuration of the PV system.

The Net Present Cost (NPC) calculated for the project is $1,516,227, refer to Fig. 7. The NPC accounts for all the possible costs incurred to procure and set up the complete power plant, replacement cost of the new equipment, operation and maintenance (O&M) expenses, and Fuel. The computed NPC is dominated by the system set-up cost, 46%, followed by diesel fuel expenses which stood at 26%. The fuel and the O&M cost are much higher than the general standard due to the offshore location of the fish farm. The accessibility of resources at the remote site is a challenging task, so the cost is considered accordingly. Levelized Cost of Energy is the analysis that looks at the lifetime energy cost and lifetime energy production from an economic perspective [19]. The LCOE considers all costs associated with a power generation facility, including initial capital expenditures, ongoing operating and maintenance expenses, fuel costs, and estimated lifespan energy output. The LCOE offers a standardized technique to compare the cost-competitiveness of various energy sources or technologies by dividing the total costs by the total energy generated. LCOE computed for this case is $0.4935 and can be represented as an equation as follows [20].

$$LCOE = \frac{Total\ Cost}{AC\ Load + DC\ Load} \tag{2}$$



Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
CanadianSolar MaxPower CS6U-340M	$484,872.87	$0.00	$69,646.69	$0.00	$0.00	$554,519.56
CAT-100kVA-50Hz-PP	$0.00	$0.00	$140,586.74	$398,066.58	($157.21)	$538,496.12
SUNSYS PCS² OG 100kVA TL	$17,724.81	$9,395.26	$114.57	$0.00	($1,273.84)	$25,960.81
Trojan SAGM 12 105	$195,000.00	$127,136.24	$75,625.97	$0.00	($511.64)	$397,250.57
System	$697,597.68	$136,531.50	$285,973.97	$398,066.58	($1,942.68)	$1,516,227.05

Fig. 7. Cost summary.

The cash flow summary, referred to in Fig. 8, gives a snapshot of the amount required to establish and run the project expended over the lifetime of the project i.e. 25 years.

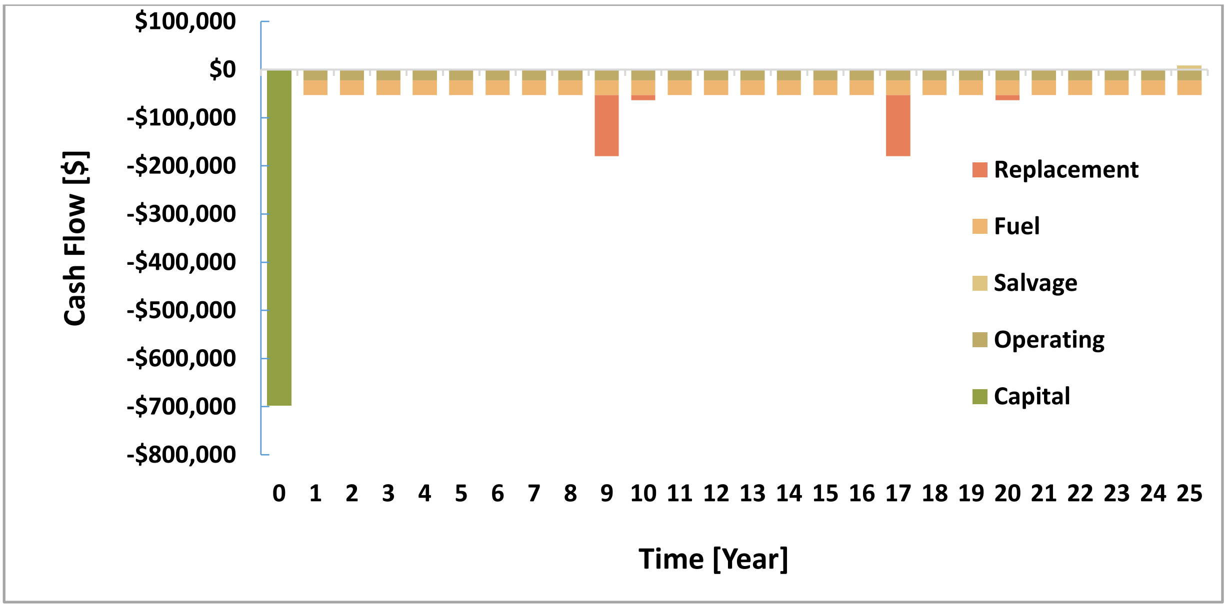


Fig. 8. Cash flow summary.

3.3. Ideal Case

The description of the Ideal case is as follows.

- The annual average per day solar resource is increased to 10% (3.30 kWh/m^2/day) and the annual average per day load is decreased by 10% (586 kWh/day).

The monthly electricity production, referred to in Fig. 9, shows that more than 89% of the power is generated by the installed solar plant and only 10% of power reliance is on diesel generator. The renewable penetration is found to be 78.3%. The total computed PV capacity is 289 kW, 850 No. of Panels of 340 W. The battery bank is 500.4 kWh, consisting of 12 parallel strings with each string having 30 batteries. The NPC of the system is $1,278,775 with LCOE of $0.4624.

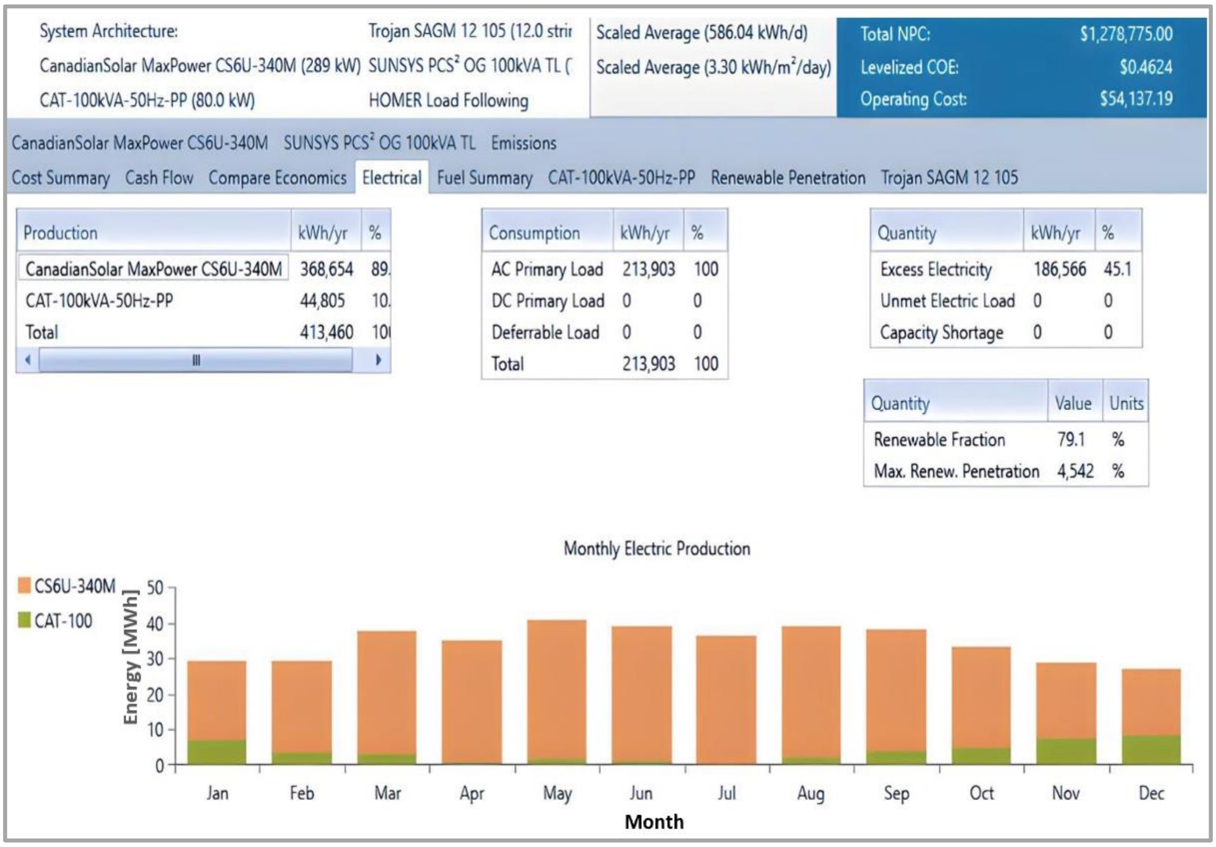


Fig. 9. Monthly electricity production by PV and Generator (10% Less Load and 10% more solar insolation level).

3.4. Worst Case

The worst-case scenario has the following assumptions.

- The annual average per day solar resource decreased to 10% (2.70 kWh/m^2/day) and the annual average per day load increased by 10% (716 kWh/day).

The monthly electricity production, referred to in Fig. 10, shows that more than 91% of the power is generated by the installed solar plant and only 8% of power reliance is on diesel generator. The renewable penetration is found to be 85%. The total computed PV capacity is 461 kW, 1356 No. of Panels of 340 W. The battery bank is 1000.8 kWh, consisting of 24 parallel strings with each string having 30 batteries. The NPC of the system is $1,764,691 with LCOE of $0.5223.

Fig. 10. Monthly electricity production by PV and generator (10% more load and 10% less solar insolation level).

4. DISCUSSION

The designed system's production capability is tested under various conditions and all three cases prove that it has the absolute capability to provide electricity to the offshore fish farm. Further, the renewable penetration in all three cases is substantial and it is evident that energy reliance of offshore aquaculture can easily be shifted from fossil fuel to environmentally friendly energy resources. The usage of renewable energy sources shall be a great step to protect the environment and a significant help to reduce global warming.

The diameter of one fish cage is 50.95 m and its area is 2039 m². The dimensions of the selected PV plate are 1960x992x40 mm and the area of one plate is 2m². Considering the Base Case, 1077 No of PV panels shall be required which can be installed comfortably on two cages following the scheme referred to in Fig. 11.

Fig. 11. FSPV installation scheme.

The economic viability of the proposed system is also investigated by analyzing and comparing the cost of electricity production of existing (three diesel generators each of 99 kVA) and the proposed power system infrastructure. The actual fuel consumption data of these generators for different months of the year 2022 is taken from the project site to calculate the Cost of Electricity (COE), refer to Table 2. Since the price of diesel varies so, the average price prevailing in the vicinity of St. John's for March 2023-June 12, 2023 is taken. There is a colossal cost associated with the transportation of diesel at fish a farm site therefore, its impact is also accounted for in the calculations.

Table 2. COE with existing system (three diesel generators, 99 kVA each).

Description	Day					
	Jan 22	Feb 22	May 22	Jun 22	Jul 22	Dec 22
Monthly Fuel Consumption of Three Gen, L	8970	9034	9246	9600	9660	9142
Per day Fuel Consumption of Three Gen, L	299	301	308	320	322	305
Fuel Cost per liter [USD]	1.80					
Per day fuel cost [USD]	538	542	555	576	580	548
Average Load [kWh]	651.5					
COE/kWh [USD]	0.83	0.83	0.85	0.88	0.89	0.84

The annual average COE/kWh comes out to 0.85 USD whereas if we take the base case of the proposed system the LCOE is 0.4935 USD. An important point to focus on is that while calculating the (COE)/kWh for the existing system, the capital, replacement, auxiliary equipment (cables, switchgear, etc.), and O&M cost are not considered and only fuel cost is taken into calculation whereas LCOE accounts for all the said costs. Despite this significant leverage and ignorance of cost extended to the current system, the proposed FSPV system is 42% cost-effective, which portrays a difference that cannot be overlooked. Due to the remote/offshore location of the fish farm, the replacement and O&M cost of the diesel generators is way higher than general prevailing standards and if that is included then the gap is expected to widen up to 50%.

5. CONCLUSIONS

The above-stated analysis provides a strong basis to conclude that the FSPV systems can be a great source to provide economical and environmentally friendly energy to the offshore fish farm which is located in Newfoundland, Canada. By using FSPV systems, fish farms can reduce their carbon footprint and contribute to a more sustainable environment. In addition, FSPV systems require minimal maintenance and can last for several years with proper upkeep, making them a reliable and low-maintenance source of energy for fish farms.

Offshore fish farming requires a reliable source of electricity to power feed blowers, aerators, and other equipment necessary for fish growth and maintenance. The provision of low-cost energy shall be a pinnacle transformation to bring sustainability, improve profitability, and expand the Canadian aquaculture industry that will proceed to assist in boosting the economy and meeting the food security challenges for the ever-growing population.

The FSPV can be a game-changer for the aquaculture industry, and it has all the potential to improve the sustainability of the business by providing economical and environmentally friendly energy.

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