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Optimal planning and design of waste-to-energy plant for aquaculture systems

Desmond Eseoghene Ighravwe[1*], Akpevweoghene Solomon Abijah[2], Daniel Osezua Aikhuele[3], Sunday Thomas Ajayi[1], Johnson Adeleke Adeyiga[4]

[1]Department of Mechanical Engineering, Bells University of Technology, Ota, Nigeria
[2]University of Limerick, Castletroy, Limerick, V94 T9PX, Ireland
[3]Department of Mechanical Engineering, University of Port-Harcourt, Nigeria
[4]Department of Computer Science and Information Technology, Bells University of Technology, Ota, Nigeria

Abstract

Background: Several aquaculture industries in underdeveloped nations use fossil fuel-powered generators to produce electricity. This pattern has raised greenhouse gas emissions as well as the price of aquaculture products.

Methods: To address this issue, this study contains a bi-objective model that optimizes the parametric settings of waste-to-energy (WTE) plants for aquaculture firms: Levelized cost of energy and power expenses for reverse logistics. The best values for these objectives were created using a genetic algorithm and goal programming.

Results: Four planning periods were taken into account during implementation, and actual data were gathered from a Nigerian aquaculture company. The electricity costs from biodiesel ranged from ₦0.7541 per kW to ₦0.7628 per kW, respectively. Reverse logistics has energy costs ranging from ₦6 329 492.10 to ₦7 121 015.53. The proposed model produced average values for several WTE parametric parameters, including a 1.69 million kg hydrogen gas, a 59.16% hydrogen gas compression efficiency, and an 83.39% electricity conversion efficiency. Furthermore, the system had logistics' minimum and maximum fractions of 0.18% and 21%, respectively.

Conclusion: Our findings demonstrated how WTE parametric parameters impact the aquaculture industry's electrical power unit.

Keywords: Algorithm, Aquaculture, Electricity, Hydrogen, Nigeria

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***Correspondence to:**
Desmond Eseoghene Ighravwe,
Email: ighravwedesmond@gamil.com

Introduction

Aquaculture is one of the most profitable industries in several emerging nations because it has high returns on investment. Given the rate of population expansion, this company's products will become more in demand (1). Unfortunately, several aquaculture businesses need constant electrical supplies to meet local and foreign clients' product demands. For aquaculture to be sustainable, electricity must be available to run the cooling systems in a farm and other equipment (such as air conditioners, electric lamps, palletizers, mixers, and dryers). Most African aquaculture operations use fossil fuel generators to power the above-mentioned machines (2). Their dependence on fossil fuels contradicts the idea of clean production; hence, there is a need to motivate stakeholders in this industry to increase clean energy resources in their energy mix.

The increased utilization of clean energy resources has several benefits for aquaculture businesses. First, it will boost production rates. By using clean energy sources, such as biogas, aquaculture businesses can reduce their reliance on traditional energy sources. This will lead to cost-effectiveness operations. Second, clean energy adoption will help to reduce greenhouse gas emissions associated with aquaculture activities. By transitioning to cleaner energy, these businesses can minimize their carbon footprint. Third, the increased utilization of clean energy resources in aquaculture will create new job opportunities. For instance, the development, installation, and maintenance of clean energy infrastructure, such as a waste-to-energy (WTE) plant, require a workforce, thus, stimulating job growth and providing economic benefits to local communities. Lastly, the shift towards clean energy resources in aquaculture can lead to improved community health outcomes. By reducing the use of these pollutants and transitioning to cleaner energy, aquaculture businesses contribute to cleaner air and water, reducing health risks, and improving the well-being of surrounding communities (3).

Currently, there are numerous energy sources for clean production in the aquaculture industry, but biodiesel, a WTE plant byproduct, stands out due to its particular advantages (4). Integrating biodiesel into the aquaculture industry's energy mix, accurately forecasting biodiesel production, and converting food waste into electricity are just a few advantages. The optimization of WTE plant operational parameters for aquaculture firms is a topic on which little information is available. Hydrogen gas compression efficiency, power consumption, electricity conversion efficiency, and hydrogen gas are some factors that must be optimized (5,6). Scholars must specify an objective for the optimization process to produce precise operational values for WTE plants to optimize these parameters. Previous research on these topics has focused solely on producing operational values for WTE plants, ignoring the unique requirements of systems that depend on electricity. For instance, Ayodele et al (7) examined specific places to generate electricity from food waste in Nigeria. They demonstrated a direct correlation between the amount of energy produced by a WTE plant and the amount of hydrogen gas produced by the process.

The energy planning problem is complex because of the intricate relationship among the planning parameters. Hence, non-linear models have been developed to optimize the parameters for energy planning. For instance, Akinyele et al (8) discussed the significance of looking at a community's energy use from both productive and unproductive angles. A nonlinear mathematical model was employed to create the data used in this investigation. In a different study, Serrano-Arévalo et al (9) presented a Pareto diagram used to examine the relationship between water use and economic and hazardous gas emissions. They believed reducing water use and damaging gas emissions could lead to environmental sustainability. An article on electricity planning in a cogeneration scenario is presented in the study of Oh et al (10). The energy requirements for heating and cooling were calculated using economic indicators such as payment period and return rate. Their model shows that a cogeneration strategy can reduce fuel tariffs.

To enhance the analysis of the optimal dispatch problem, Guo et al (11) used the connection between the demand for cooling and heating. They presented a thorough investigation of the effects of a backup heating source during a shortage in electricity supply using a genetic algorithm and nonlinear modeling approach. A bi-objective model for regional energy demand is presented in the study by Pan et al (12). Their model enhances analyses of hydrogen's levelized cost and penetration of renewable energy sources. For various hydrogen demands, for instance, their model produced a lower levelized cost of energy than a single-objective model. Maroufmashat et al (13) conducted a study to enhance an urban community's energy plan. This study examined the hydrogen economy in light of energy efficiency and storage system issues using a nonlinear multi-objective model. A summary of their findings demonstrates the significance of distributed energy resources (DER) in a smart community's energy consumption.

Calvillo et al (14) considered the energy market participants' roles in the best-case scenario planning of DER. They were able to describe how policymakers' actions affected these resources. Additionally, they noticed that a stochastic approach to these resources produces a more responsive price reaction than a deterministic strategy. The effects of customers adopting DER on improving microgrid management are explained in the study by Jung and Villaran (15). They observed the effectiveness of microgrid systems with customers adopting DER when environmental and economic aspects explained this adoption. Quashie et al (16) analyzed the significance of cooperative DER and distribution system operator optimization. The optimization was done using a bi-objective modelling strategy. The outcomes of this method were utilized to support the inclusion of energy storage systems in microgrid management.

Researchers have established the importance of energy storage systems and hydrogen gas for environmental preservation and energy mix. However, using hydrogen gas and energy storage devices to meet aquaculture firms' energy needs to be better understood. As a result, this study proposes a bi-objective model for aquaculture business energy management. The energy storage system in the model was an inverter, and hydrogen gas from a WTE system was considered.

The use of a non-linear optimization strategy in this study to resolve the energy-mix problem, is one of the advantages of this study. This method generates useful information that will enable decision-makers to make informed and logical decisions because it considers different variables. Using this method, the study successfully develops compromise solutions for the price of electricity, the cost of hydrogen gas, and the efficiency of electricity conversion. Also, this study's emphasis on the optimization of energy usage for reverse logistics in the aquaculture business is another advantage. The study will improve sustainability in the agro-business industry by optimizing energy use in the context of reverse logistics. Furthermore, the study emphasizes on WTE is another advantage because of the environmental and human health benefits that come from waste management.

Materials and Methods

A closer look at the literature highlights some of the shortcomings of WTE plant utilization. The proposed models in goal programming and the genetic algorithm are novel analytical methods for optimization problems. Goal programming is a modification of linear programming used to deal with numerous, usually opposing, objective measures. For example, the government promises to increase the goods produced within the country and, at the same time, increase the tax paid by small and medium enterprises. Finding only one solution that optimizes the opposing goals is necessary. In this scenario, goal programming helps find a compromise solution because of all the objectives (17).

The genetic algorithm (GA) has become an increasingly important optimization tool for researchers to address NP-hard problems because it can produce feasible solutions quickly (17). A genetic algorithm generates optimal solutions for optimization problems, particularly problems with nonlinear relationships. It is a bio-inspired meta-heuristic that mimics the survival of the fittest concept while generating high-quality solutions to optimization and research problems by depending on bio-inspired operators such as mutation, crossover, and selection (8,18). It is based on the Darwin's evolutionary theory of the survival of the fittest. Each possible solution to the problem can be regarded as an individual in a natural population. The next candidate set of solutions is created using a few activities, including crossover, mutation, and reproduction (19).

Model formulation

The proposed model is developed to address the following goals:

- To estimate an aquaculture system's energy demand.
- To determine the optimal cost of energy.
- To determine the optimal cost of electricity for reverse logistics.
- To compare the hydrogen gas compression efficiency and electricity conversion efficiency.
- To quantify the volume of hydrogen gas needed for electricity generation.
- To estimate the fraction of energy for reverse logistics.
- To determine the total electricity generated per period.

The proposed model uses the following assumptions to develop the proposed bi-objective optimization model for WTE plant sizing:

The annual energy consumption of an aquaculture business is known.

Electricity from a generator, national grid, and biodegradable sources can power an aquaculture business. The model's first objective function is the levelized cost of energy (LCOE). Equation (1) gives the mathematical expression for this cost (20).

$$LCOE = \frac{\sum_{t=1}^{T}\left(I_t + \sum_{i=1}^{S} M_{it}\right) + D}{(1+r)^t \sum_{t=1}^{T}\left(\frac{\sum_{i=1}^{S} c_{it} S_t}{(1+r)^t}\right)} \tag{1}$$

This cost considered is taken as a function of the investment cost (I_t), the operation and maintenance cost (M_{it}), the decommissioning cost of the WTE plant (D), and the cost of electricity (20).

The second objective function is to minimize the energy for reverse logistics in an aquaculture system (Equation 2).

$$\sum_{t=1}^{T}\sum_{s=1}^{S} R_{st} E_{st}^{r} \lambda_{st} \tag{2}$$

This study uses the energy required for refrigeration and non-refrigeration activities to determine an aquaculture business energy demand (Equation 3).

$$E_{st} = E_{st}^{r} + E_{st}^{l} \tag{3}$$

An arithmetic progression is used to model an aquaculture system's periodic increase in energy demand. Equation (4) expresses energy for refrigeration activities in a sub-period. Similarly, the expression for energy for non-refrigeration activities in a sub-period is given as Equation (5).

$$E_{st}^{r} = E_{0s}^{r} + (t-1) d^{r} \tag{4}$$

$$E_{st}^{l} = E_{0s}^{l} + (t-1) d^{l} \tag{5}$$

where, E_{0s}^{r} and E_{0s}^{l} denote the initial energy demand for refrigeration and non-refrigeration activities in sub-period *s*, respectively (kW), d^r and d^l denote the rate of change in energy demand for refrigeration and non-refrigeration activities at sub-period *s* in year *t*, respectively (kW).

Given that an aquaculture system accepts reverse logistics, the expected fraction of energy for reverse logistics is added to Equation (4), and it becomes Equation (6).

$$E_{st}^{r} = (1 + R_{st}) E_{0s}^{r} + (t-1) d^{r} \tag{6}$$

where R_{st} denotes the expected fraction of energy for reverse logistics in sub-period *s* in year *t*.

Equation (7) expresses the total energy demand for an aquaculture system.

$$\sum_{t=1}^{T}\sum_{s=1}^{S}\left((1+R_{st}) E_{0s}^{r} + (t-1) d^{r} + E_{0s}^{l} + (t-1) d^{l}\right) \tag{7}$$

The relationship between energy supply, energy demand, and stored energy is given as Equation (8) expresses energy demand per year.

$$\sum_{s=1}^{S}\left((1+R_{st}) E_{0s}^{r} + (t-1) d^{r} + E_{0s}^{l} + (t-1) d^{l}\right) = S_t \qquad t \in T \tag{8}$$

The energy stored in a sub-period is expressed as Equation (9).

$$S_t = \sum_{s=1}^{S}\left(S_{st} + F_{st}\right) \qquad t \in T \tag{9}$$

A binary variable estimates the amount of energy stored in a sub-period (Equation 10).

$$f_{st} = \begin{cases} 1 & if\ (1+R_{st})E^{r}_{0s} + (t-1)d^{r} + E^{l}_{0s} + (t-1)d^{l} < S_t \\ 0 & otherwise \end{cases} \quad s \in S; t \in T \quad (10)$$

Equation (11) gives the expected average system failure for the energy planning problem.

$$\frac{1}{T}\sum_{t=1}^{T}\frac{1}{S}\sum_{s=1}^{S}F_{st} \le \bar{f} \quad (11)$$

$$F_{st} = \left(S_t - (1+R_{st})E^{r}_{0s} + (t-1)d^{r} + E^{l}_{0s} + (t-1)d^{l}\right)f_{st} \quad s \in S; t \in T \quad (12)$$

where, $\bar{f}$ denotes the expected energy stored in a planning period (kW).

Equation (13) gives the expression of energy from a WTE process (21).

$$S_{st} = \frac{AH_{2st}\eta_{1st}}{H_{2CD}} \times LHV \times \eta_{2st} \times H_D \quad t \in T, s \in S \quad (13)$$

$$S_{st} = (1-y_{st})\left(\frac{AH_{2st}\eta_{1st}}{H_{2CD}} \times LHV \times \eta_{2st} \times H_D\right) \quad t \in T, s \in S \quad (14)$$

where, y_{st} denotes the system's failure rate in sub-period s and period t, η_{1st} and η_{2st} denote hydrogen gas compression and electricity conversion efficiencies respectively in sub-period s at year t, AH_{2st} denotes the quantity of hydrogen gas produced in sub-period s at year t, LHV denotes the lower heating value of hydrogen gas, H_{2CD} denotes the density of compressed hydrogen (21).

The expected average energy produced from the WTE process is expressed as Equation (15).

$$\frac{1}{S}\sum_{s=1}^{S}S_{st} \ge E_{\min} \quad t \in T \quad (15)$$

where $E_{\min}$ denotes the expected average energy produced from the WTE process (kW).

In this study, the annual energy cost from this process is expressed as Equation (16).

$$\sum_{s=1}^{S}C_{st}S_{st} \le B_t \quad t \in T \quad (16)$$

Where B_t denotes the budgeted fund for electricity generation at period t (₦) and C_{st} denotes the unit cost of generated electricity (₦).

Equations (17) to (21) give the boundary constraints for the decision variables.

$$\eta_1^{\min} \le \eta_{1st} \le \eta_1^{\max} \quad s \in S; t \in T \quad (17)$$

$$\eta_2^{\min} \le \eta_{2st} \le \eta_2^{\max} \quad s \in S; t \in T \quad (18)$$

$$A_{\min} \le AH_{2st} \le A_{\max} \quad s \in S; t \in T \quad (19)$$

$$R_{\min} \le R_{st} \le R_{\max} \quad s \in S; t \in T \quad (20)$$

$$y_{\min} \le y_{st} \le y_{\max} \quad s \in S; t \in T \quad (21)$$

The equations for the suggested bi-objective optimization model are presented in Equations (1) to (21). This model is innovative since it incorporates energy consumption factors for reverse logistics in WTE systems. This addition broadens the model's scope by addressing a crucial issue that was previously ignored. By particularly tailoring the WTE systems' operational characteristics for the aquaculture industry, this study also offers another uniqueness. The study offers important insights and ideas that might boost the effectiveness and sustainability of WTE operations in this industry by adapting the optimization process to the particular needs and limitations of the aquaculture industry.

Case Study

The model's performance was evaluated based on the data collected from two aquaculture farms in Nigeria. The first farm is a small-scale establishment dealing with fish farming and cassava cultivation; it produces fish feed using specialized equipment. They are recycled waste; for example, the cassava plant is also used as fish feed, and fish waste is used as organic fertilizer for cassava. The second farm is a medium-scale establishment of farming activities, ranging from fish farming, cassava cultivation, poultry, piggery, and heliciculture (snail farming), to vegetable cultivation. Based on the data obtained, farm B was selected as the case study for the model's implementation. It produces its feed with specialized and modernised equipment, such as location 1, which is also involved in recycling waste. It also uses energy savings and management through the total and thorough utilization of energy by using energy-saving bulbs and solar appliances. After collecting the required data, the model was used to generate optimal values for the decision variables (Equations 17 to 21). Because the model contained several nonlinear relationships, it was solved using GA. This algorithm's ability to handle nonlinear relationships has been documented in the literature (8,11,22).

Results

Table 1 presents the electricity cost for reversed logistics in different years based on the GA results. The optimal values for the hydrogen gas compression efficiency are presented in Table 2.

Table 3 shows the optimal values for the electricity conversion efficiency, while the optimal values for hydrogen gas production are presented in Table 4.

Tables 5 and 6 present the optimal values for a fraction of electricity for reverse logistics and generated electricity, respectively.

Figure 1 shows that subperiods 2 and 1 had the lowest and highest hydrogen gas compression efficiencies, respectively.

Table 1. Optimal values for the cost of energy per kW (₦)

Year 1	Year 2	Year 3	Year 4
0.7612	0.7541	0.7628	0.7572

Table 2. Optimal values for reverse logistic electricity cost (₦)

Year 1	Year 2	Year 3	Year 4
6,783,077.74	7,121,015.53	6,671,884.29	6,329,492.10

Table 3. Optimal values for electricity conversion efficiency (%)

Year	Sub-period 1	Sub-period 2	Sub-period 3	Sub-period 4
1	83.97	84.44	84.31	82.98
2	83.17	83.85	82.48	83.89
3	82.95	83.81	82.05	82.59
4	83.47	83.09	84.34	82.74

Table 4. Optimal values for hydrogen gas (million kg)

Year	Sub-period 1	Sub-period 2	Sub-period 3	Sub-period 4
1	1.69	1.69	1.69	1.69
2	1.70	1.70	1.70	1.70
3	1.68	1.68	1.68	1.68
4	1.68	1.68	1.68	1.68

Table 5. Optimal values for a fraction of electricity for reverse logistics (%)

Year	Sub-period 1	Sub-period 2	Sub-period 3	Sub-period 4
1	0.18	0.20	0.21	0.20
2	0.18	0.18	0.18	0.19
3	0.20	0.19	0.20	0.19
4	0.18	0.20	0.18	0.18

Table 6. Optimal values for electricity generated (million kWh)

Year	Sub-period 1	Sub-period 2	Sub-period 3	Sub-period 4
1	0.57	0.56	0.55	0.57
2	0.58	0.57	0.56	0.56
3	0.56	0.57	0.52	0.59
4	0.56	0.54	0.56	0.60

Figure 2 shows that the system's average electricity conversion efficiency is 83.38%.

Figure 3 shows the statistics for the electricity used for reverse logistics.

Figure 4 shows the statistics for electricity generated by the system.

Discussion

Energy cost

The average electricity cost is ₦0.7588 per kW. The lowest electricity cost among the years considered was ₦0.7541 per kW, which occurred in Year 2. The highest electricity cost (₦0.7628 kW) was reported in Year 3. There was a 0.93% decrease in the electricity price in Year 2 when Year 1 was used as a base year. In Year 3, there was a 1.14% increase in electricity cost, while there was a 0.73% decrease in electricity cost in Year 4 (Table 1).

The total electricity cost for reverse logistics is ₦26 905 469.66, while the reverse logistics average electricity cost was ₦6 726 367.42 (Table 2). The lowest electricity cost for reverse logistics was reported in Year 4, whereas the highest electricity cost for reverse logistics

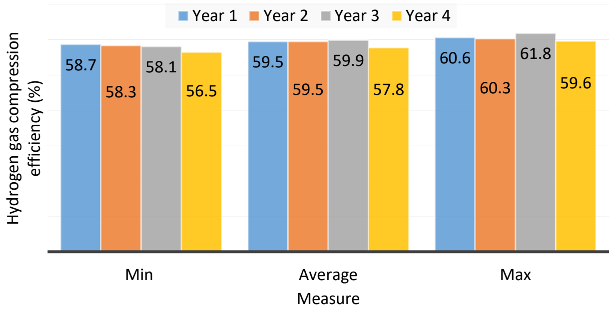

Figure 1. Statistics for the hydrogen gas compression efficiency

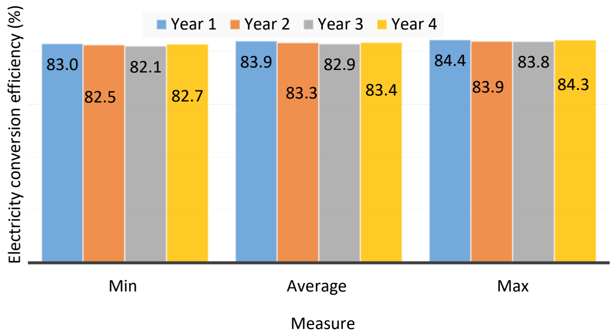

Figure 2. Statistics for the electricity conversion efficiency

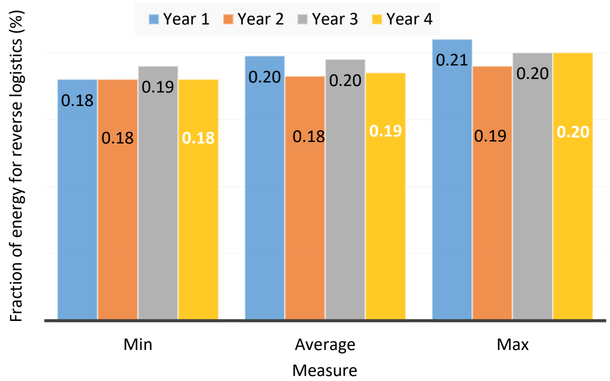

Figure 3. Statistics for a fraction of electricity for reverse logistics

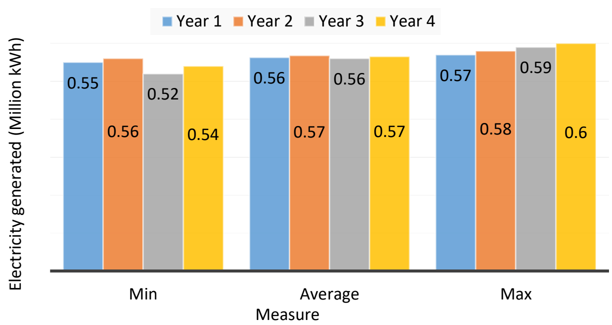

Figure 4. Electricity generated for the system

was reported in Year 2. There was a 4.75% (₦7 121 015.53) increase in electricity costs for reverse logistics in Year 2 using Year 1 as a base year. Regarding the change in the electricity cost for reverse logistics, a 6.3% decrease in this cost was observed in Year 3 (₦6 671 884.29), whereas a 5.13% decrease (₦6 329 492.10) for this electricity cost was reported in Year 4.

Hydrogen gas compression efficiency

Table 3 shows that in Year 1, the lowest and highest electricity conversion efficiencies occurred in sub-periods 4 and 2, respectively. The analysis for Year 1 shows that it has an average efficiency of 83.95%. Sub-period 3 had the lowest electricity conversion in the second year, whereas sub-period 4 had the highest efficiency. The second-year average efficiency was 83.35%. The third-year results showed that sub-period 3 had the lowest electricity conversion efficiency, sub-period 2 had the highest efficiency, and its average efficiency was 82.85%. In the fourth year, the lowest electricity conversion efficiency occurred in sub-period 4, whereas the highest one occurred in sub-period 3. Table 3 shows that the fourth-year average efficiency was 83.41%.

Hydrogen gas

In Year 1, the average hydrogen gas compression of the system was 59.52%. Sub-period 1 had the lowest hydrogen gas compression efficiency, whereas sub-period 2 had the highest hydrogen gas efficiency (Table 4). In Year 2, the average hydrogen gas compression efficiency was 59.47%. In this year, the lowest hydrogen gas compression efficiency occurred in sub-period 1, whereas the highest hydrogen gas compression efficiency was in sub-period 4. In Year 3, the average hydrogen gas compression efficiency was 59.86%. Subperiods 2 and 1 had the lowest and highest hydrogen gas compression efficiencies, respectively (Figure 1).

Electricity conversion efficiency

The case study's statistics on electricity conversion efficiency show that years 3 and 4 had the lowest and highest efficiencies, respectively. In terms of average efficiency, Year 3 had the highest value. An analysis of the results in Figure 2 shows that the system's average electricity conversion efficiency is 83.38%.

Fraction of electricity for reverse logistics

Table 5 shows that the fraction of electricity used for reverse logistics in sub-periods 1 and 3 had the lowest and highest values, respectively, in Year 1. On the other hand, the highest amount of electricity for reverse logistics in Year 2 occurred in subperiod 4. The remaining periods have the same electricity for reverse logistics (Table 5). In Year 3, the same amount of electricity was used for reverse logistics in subperiods 1 and 3. The same electricity was used for reverse logistics in sub-periods 2 and 4 in Year 3. The electricity distribution for reverse logistics in Year 4 is similar to that in Year 2, but its highest value occurs in sub-period 2 (Table 5). As shown in the figure 3, the logistics' minimum and maximum fractions are 0.18% and 21%, respectively.

Generated electricity

In the first year, the lowest electricity generation occurred in sub-period 3, and its highest electricity generation occurred in sub-periods 1 and 4 (Table 6). The lowest electricity generation occurred in sub-periods 3 and 4 in the second year, whereas the highest electricity generation occurred in period 1. Year 3 had the lowest and highest electricity generation values during periods 3 and 2. In the fourth year, the system generated the highest electricity in sub-period 4 and the lowest one in sub-period 2.

In the figure 4, the average amounts of electricity generated in years 1 and 3 were the same, and similarly, the average electricity generated in years 2 and 4 was the same. Based on this figure, the maximum amount of electricity generated in a sub-period occurred in Year 4, and the minimum amount of electricity generated occurred in Year 3 (Figure 4).

Conclusion

This study used a nonlinear model technique to maximize electricity use for medium-scale aquaculture in Nigeria. This study was conducted to estimate the electricity consumption for aquaculture, minimize an aquaculture system's levelized cost, and minimize the overall electricity cost of reverse logistics in an aquaculture system. Two aquaculture companies in Nigeria were considered for evaluation and validation. The levelized energy costs for reverse logistics in an aquaculture business were optimized using a multi-objective deterministic programming approach. The model was evaluated and validated using data from Nigerian aquaculture firms. According to the results of this study, the highest and lowest electricity costs from biodiesel were ₦0.7628 and ₦0.7541 per kW, respectively. The highest and lowest energy costs for reverse logistics were ₦7 121 015.53, and ₦6 329 492.10, respectively. The average hydrogen gas compression efficiency for four years was less than the electricity conversion efficiency over the same period. The model can generate a large amount of energy with an average of 0.56 million kWh per period. These results show that the proposed model can be used to explore the different parametric settings for the case study. In the future, we plan to include the total production of this system. In addition, some deterministic constraints were converted to stochastic constraints.

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Authors' contributions

Conceptualization: Desmond Eseoghene Ighravwe and Akpevweoghene Solomon Abijah.
Data curation: Desmond Eseoghene Ighravwe, Akpevweoghene Solomon Abijah, Daniel Osezua Aikhuele, Sunday Thomas Ajayi, Johnson Adeleke Adeyiga.
Formal analysis: Desmond Eseoghene Ighravwe, Akpevweoghene Solomon Abijah, Daniel Osezua Aikhuele, Sunday Thomas Ajayi, Johnson Adeleke Adeyiga.
Investigation: Desmond Eseoghene Ighravwe, Akpevweoghene Solomon Abijah, Daniel Osezua Aikhuele, Sunday Thomas Ajayi, Johnson Adeleke Adeyiga.
Project administration: Desmond Eseoghene Ighravwe, Daniel Osezua Aikhuele.
Resources: Desmond Eseoghene Ighravwe, Akpevweoghene Solomon Abijah, Daniel Osezua Aikhuele, Sunday Thomas Ajayi, Johnson Adeleke Adeyiga.
Software: Johnson Adeleke Adeyiga.
Validation: Daniel Osezua Aikhuele.
Visualisation: Desmond Eseoghene Ighravwe, Akpevweoghene Solomon Abijah.
Writing – original draft: Desmond Eseoghene Ighravwe, Akpevweoghene Solomon Abijah, Daniel Osezua Aikhuele, Sunday Thomas Ajayi, Johnson Adeleke Adeyiga.

Competing interests

The authors declare that there is no conflict of interests.

Ethical issues

This paper does not contain ethical issues.

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