IMPROVING THE ENVIRONMENTAL PERFORMANCE OF FISH-FARMING HOUSES: A COMPARATIVE PASSIVE DESIGN STUDY IN SOUTH KOREA

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ABSTRACT

Aquaculture in South Korea largely involves crudely-built plastic fishery houses that consume excessive electricity and produce carbon emissions. This study explores a potential method to make Korean aquaculture more sustainable by suggesting design alternatives that can save energy and costs. To this end, the authors compare the energy use and indoor environments of three different designs through field mockups. The three designs include (i) a triple-layered plastic screen house (Design 1), (ii) an insulated vault house (Design 2), and (iii) a passive-house design (Design 3), in addition to (iv) a single-layered plastic house (baseline). Our findings indicate that, compared to the baseline, operational electricity was reduced to 57.81% in Design 1, 53.92 % in Design 2, and 40.59% in Design 3. Moreover, Designs 2 and 3 were able to mitigate indoor temperature fluctuations in winter. Design 1 showed a relatively unstable temperature distribution during the night but offered better farming conditions than the baseline. Humidity often rose to 100% but did not affect the maintenance of a desirable fish and workplace environment. Even a high concentration of carbon dioxide of up to 3,000 ppm in Designs 1 and 2 was not expected to harm farmers' health. Cost analyses revealed that construction expenses increased to 20.9% in Design 1, 135.8% in Design 2, and 73.9% in Design 3 due to large quantities of materials and labor. Considering trade-offs with energy saving, the payback period is 7.2 years for Design 1, 35.5 years for Design 2, and 17.9 years for Design 3. Given that the lifetime expectancy of Designs 1 and 3 is over two years, the study's results confirm that Designs 1 and 3 have a comparative advantage in producing sustainable fish-farming houses.

KEYWORDS

passive house, Building performance, fish-farming house, aquaculture, sustainability

1. INTRODUCTION

In Southeast Asia, the aquaculture industry has played an increasingly important role in fisheries, particularly as recent catch profiles face downturns due to widespread oceanic environmental

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pollution and the resulting downsizing of marine products. The productivity ratio of farmed fish to wild-caught fish among seafood items was 47% in 2010, and it has continued to rise since then (OECD/FAO, 2017). Fish-farming facilities, in general, require vast amounts of energy to provide water ponds and fish cages with optimal environmental conditions (temperature, oxygen, light, etc.). In South Korea, however, crudely-assembled farming houses with a single layer of metal-framed plastic screens make fish farming wasteful in terms of energy and prone to environmental perturbation. Although the simple construction might save costs at first, the excessive energy use of plastic farming houses undermines the potential of sustainable aquaculture, increasing long-term operational/maintenance expenditure.

In an effort to improve the environmental performance and sustainability of fish-farming houses, this study builds on the hypothesis that the application of the passive-house construction method and related green-building technologies helps reduce end-energy use, carbon emissions, and the houses' life-cycle cost, ultimately contributing to the mitigation of global climate change. In the building industry, prior attempts to enhance building performance have found passive-house technologies (e.g., reinforced thermal insulation, airtightness, high-performance windows, heat bridge protection, heat-exchange ventilation, etc.) effective to reduce energy consumption and environmental impacts (Hegger et al., 2008). Introducing these methods to Korean fish-farming houses, this study aims to demonstrate the green house technology's environmental and economic effectiveness in aquaculture. To this end, three different types of eel-farming houses were compared to a general single-layered plastic house in terms of indoor temperature change, manufacturing costs, operational energy, and CO_2 emissions. The three designs include 1) a house with triple-layered plastic screens, 2) a vault-structured house, and 3) a passive-design house. In the first type of house construction, performance was improved through additional insulated walls and roof frames screened in three layers to prevent heat loss. The second type of construction featured rapid on-site assembling of high-performance insulation materials. General passive-building technologies were applied to build the third design. The study offers comparative energy and cost-benefit analyses of these alternatives followed by the selection of a farming house with the highest economic feasibility and environmental sustainability.

2. RELATED STUDIES

Recent research has shown that a variety of methods can be introduced to improve the performance of uninhabited screen houses, where climate conditions need to be regulated to grow plants or animals (Ntinas et al., 2014; Wang et al., 2017). Bot et al. (2005) delivered an energy use improvement of 40% by insulating the house envelope and 60% by installing heat pumps sourced from residual indoor heat stored in the ground during the daytime throughout the cooling seasons. Kim et al. (2017) conducted an experiment using a farmer's plant house. They found that the use of laminated paper sheets, non-woven fabrics, and polyester films to thermally reinforce the plastic screen reduced energy costs up to 59% in conjunction with an air-source heat pump. Shim et al. (2017) compared the effectiveness of a multilayered heat-preserving curtain and a geothermal and water-sourced heat pump for heating with conventional oil-fueled boiler heating. The researchers identified a 61% reduction in energy use and a 77% reduction in heating costs., In a study of Korean strawberry-planting houses with a simple water-proof plastic screen, Noh et al. (2017) also argued that energy saving of around 40% can be achieved, ideally, when a package of air-source heat pump (10kW), air ducts, and multi-layered screen curtains are introduced. Kim et al. (2017) explored the energy performance of a semi-underground plastic screen house. An experimental house earth-covered in a pit of 0.6m-depth by 0.3m-length was insulated with expanded polystyrene boards (for walls under grade) and multiple polyolefin film sheets on the roof. The resulting performance was not much better than that of general screen houses, increasing indoor humidity levels to 8% during the day and 4% during the night. Lee et al. (2011) analyzed the effectiveness of solar-energy storage in a double-layered plastic green house. The researchers found that heat-exchanged daytime solar energy can be stored in a water-filled tube and that the use of this energy for overnight heating increases indoor temperature by up to 2°C. This finding suggests that approximately 80% of underground water use can be potentially saved in screened green houses.

To improve green houses' environmental performance during design and operation stages, simulation is often employed to predict and optimize the performance of uninhabited plant houses and renewable energy capacities (Shen et al., 2018). Tong et al. (2013) and Wang et al. (2014) developed a numerical analysis model for green house performance simulation, suggesting house location, roof geometry, wall thickness, and insulation materials as variables. Bot et al. (2005) used simulation to enhance energy performance and applied the results to design large-scale green houses with renewable energy supplies. It is predicted that wind turbines of 600kW capacity, 1.2 hectares land use for photovoltaic (PV) panel installation, and a biomass of 32 hectares are needed to build a 1-ha. sustainable green house.

Renewable resources play an important role in achieving energy-saving green houses. Aschilean et al. (2018) have suggested the active use of fuel cell batteries, solar radiation, and biomass to produce a sustainable green house energy system. Hassanien et al. (2018) installed translucent solar panel modules (170Wp) to over 20% of the roof area of a plastic green house, resulting in 35–40% heat reduction and 1~3°C temperature decrease while ensuring desirable humidity levels and plant growth. In addition, electricity generated by the roof solar panels enabled the operation of additional indoor conditioning systems. Cuce et al. (2016) have shown that energy savings of up to 80% are feasible by implementing various renewable energy technologies and systems, including photovoltaic modules, solar thermal collectors, hybrid systems, phase change material (PCM) and underground based heat storage techniques, energy-efficient heat pumps, alternative facade materials (e.g., heat insulation solar glass, PV glazing, aerogel and vacuum insulation panel, polycarbonate sandwich panels, etc.), innovative ventilation using pre-heating and cooling (high-performance windcatchers), and efficient lighting systems. By simultaneously monitoring PV-installed green houses and non-PV houses, Trypanagnostopoulos et al. (2017) confirmed that roof PV panels do not disrupt plant growth or development. Payback periods may cause house owners to hesitate to introduce green building systems and renewable energy devices. However, Cuce et al. (2016) found that installation payback periods are typically only four to eight years, while Wang et al. (2017) demonstrated that it only takes nine years to recoup the installation costs of PV panels.

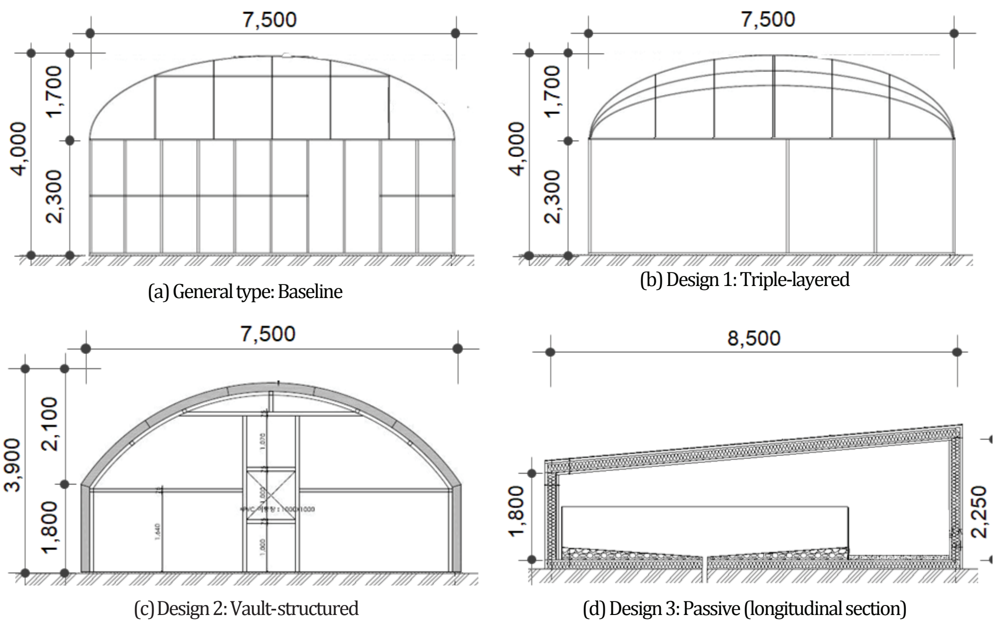
Although not many studies exist on environmentally-engineered aquaculture houses or methods to improve their building performance, research on planting greenhouses suggests the potential of the application of sustainable building technologies, systems, and equipment to fish-farming facilities. This study assumes that there is great significance in adopting passive-house designs and regulations as an alternative practice to traditional construction of fish-farming houses capable of saving operational energy and recurring costs throughout the building's life-cycle. The following sections present the study's methods and field experiment findings in investigating the characteristics and performative aspects of different fish house designs.

3. EXPERIMENT METHODS

As a pilot study, we built and analyzed a general house type and three alternative designs to improve the conventional single-layered plastic screen house. Mock-ups were installed and tested for an aquafarm farming Japanese eel in Dang-jin, South Korea (Figures 1–4). In Korea, indoor fish-farming is dominated by Japanese eels and *Anguilla japonica* (over 27%); however, the eel is known as one of the most difficult types of fish to farm, as it grows in high-temperature water

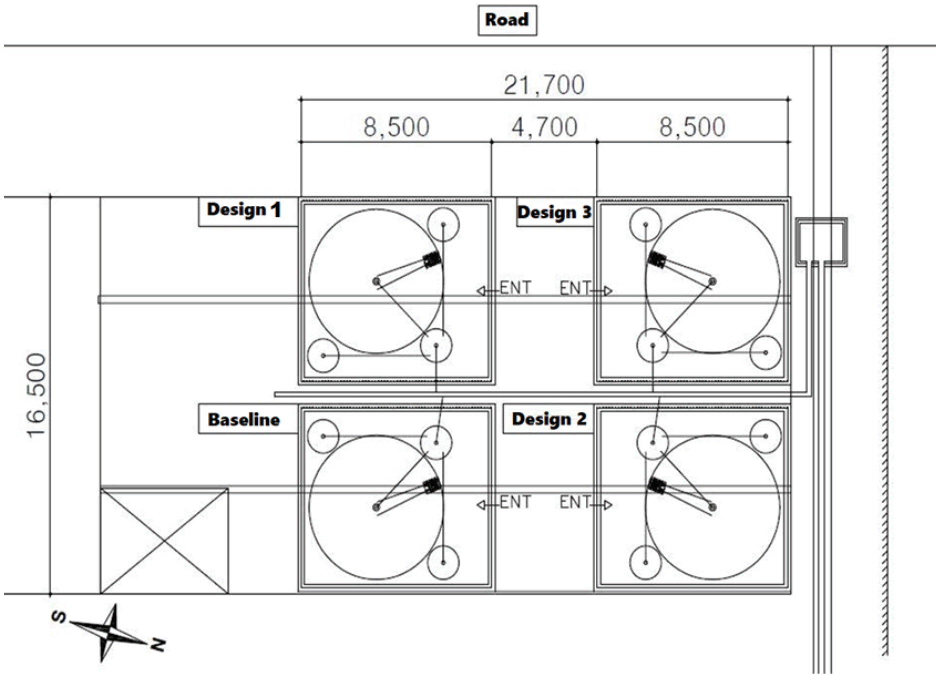
FIGURE 1. Test facility and illustration of test fish-farming house construction.

(a) Current practice: Japanese eel fish-farming (Dang-jin, South Korea)



(b) Baseline and test designs (section)

FIGURE 2. Plan and location of test mockup installation.



and therefore requires a great deal of energy to maintain such a rigorous environmental condition (Banrie, 2013). As depicted in Figure 1 (b), three different comparative designs, assumed to reduce energy consumption and costs, were suggested: (i) Design 1: a triple-layered plastic screen house, (ii) Design 2: a house of thick insulation panels with a barrel vault roof, and (iii) Design 3: a general passive-design house (Tables 1 & 2 and Figures 3 & 4). Considering life-cycle costs and operation, the two designs controlled against the passive house were assumed to

FIGURE 3. Plan (left) and interior view (right) of the Passive fish-farming house (Design 3).

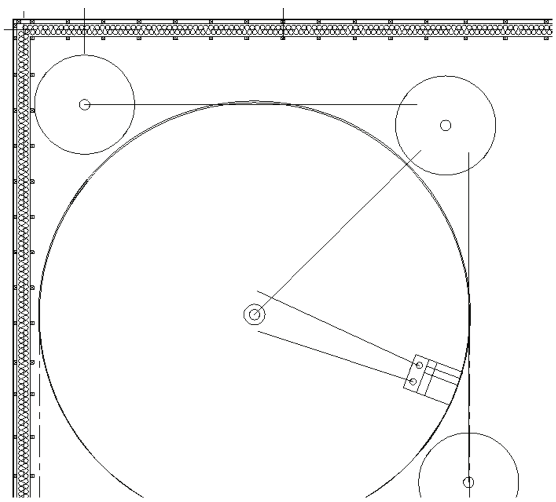


TABLE 1. Envelope material composites of the designs (inside to outside).

	Baseline	*Design 1*	*Design 2*	*Design 3*
Floor	Concrete Slab 300mm	Concrete Slab 300mm	Concrete Slab 300mm	Unreinforced (plain) concrete 100mm+XPS200mm
Wall	Single-layer plastic sheet (SLPS)	Sandwich panel 50mm	Cement mortar 3mm+XPS180mm+ Cement mortar 3mm	Metal frame 50mm+XPS180mm +metal frame 50mm+reflective insulation 5mm
Roof	SLPS	SLPS +air-gap + SLPS +non-woven cloth +air-gap + SLPS	Cement mortar 3mm+XPS180mm+ Cement mortar 3mm	Metal frame 50mm+XPS200mm +metal frame 50mm +reflective insulation 5mm

have these respective merits: the first ensures lower construction costs while the second enables quick on-site construction of the house with factory-manufactured insulation materials. The four test houses' scale was an identical 65.25m^2, the minimum size to fully cover a farming water tank (Figure 2). To ensure that each design would have the same amount of daylight and solar radiance, the houses had a clearance of 4.7m. In other words, the ratio of heights to in-between distances became one. Sandwich panels of 50mm were installed for Design 1 while non-woven fabrics and air-gaps were inserted in between the plastic roof's three layers to increase insulation. Design 2 was constructed with modular insulation assemblies of 180mm thickness and 3mm cement-mortar finish. Design 3, the passive-house, was erected on a lightweight metal frame with insulation (floor: 200mm; walls and roofs: 180mm extruded polystyrene board (XPS). The material layers of the construction assemblies are depicted in Table 2. Expected thermal performance was simulated and verified using Therm® (Figure 4 (a)).

TABLE 2. Design 3: Construction details and material properties.

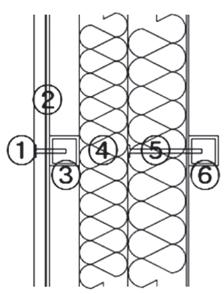
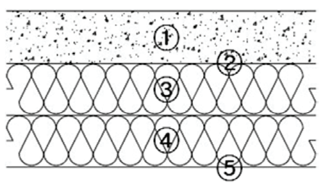
Grade wall	Lightweight metal frame	(U-value ≤ 0.15W/m^2 · K)	
		① ⑥	Polyethylene film
		②	THK 5mm heat-reflective insulation
		③	Steel pipe 50×50×1.6T, Air gap
		④ ⑤	THK 80, 100 Extruded polystyrene (XPS) foam, W040 35K (Metal stud 100×45×10, 1.3T, 610mm spacing)

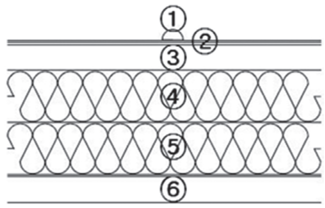
TABLE 2. *(Continued)*

Parts	Material	THK	Conductivity		Resistance	U-value	
		mm	kcal/mh°C	W/mK	$m^2h°C/kcal$	$kcal/m^2h°C$	W/m^2K
Exterior surface heat resistance					0.050	0.089	0.103
Sheathing	Polyethylene sheet	0.15	0.040	0.047	0.004		
Air	Steel pipe	50.0	0.022	0.026	2.273		
Insulation	Heat reflection	5.0	0.005	0.006	1.000		
Insulation	XPS foam board	80.0/100	0.023	0.027	3.478/4.348		
Sheathing	Polyethylene sheet	0.15	0.040	0.047	0.004		
Interior surface heat resistance					0.127		
Total		235.3			11.284		

Ground floor	Concrete	(U-value ≤ 0.15W/m^2 · K)	
		①	THK 100mm Wire mesh + plain concrete
		② ⑤	Polyethylene film
		③ ④	THK 100, 100 XPS foam board

Parts	Material	THK	Conductivity		Resistance	U-value	
		mm	kcal/mh°C	W/mK	$m^2h°C/kcal$	$kcal/m^2h°C$	W/m^2K
Exterior surface heat resistance					0.100	0.112	0.131
Finish	Plain concrete	100	1.400	1.628	0.071		
Sheathing	Polyethylene film	0.15	0.040	0.047	0.004		
Insulation	XPS board	100/100	0.023	0.027	4.348/4.348		
Sheathing	Polyethylene film	0.15	0.040	0.047	0.004		
Interior surface heat resistance					0.050		
Total		300.3			8.925		

TABLE 2. *(Continued)*

Roof	Lightweight metal frame	(U-value ≤ 0.12W/m² · K)	
		① ⑥	Polyethylene film
		②	THK 5mm heat-reflective insulation
		③	Steel pipe 50×50×1.6T, Air gap
		④ ⑤	THK 100, 100 Extruded polystyrene (XPS) foam, W040 35K (Metal stud 100×45×10, 1.3T, 610mm spacing)

		THK	Conductivity		Resistance	U-value	
Parts	Material	mm	kcal/mh°C	W/mK	m²h°C/kcal	kcal/m²h°C	W/m²K
Exterior surface heat resistance					0.100		
Sheathing	Polyethylene sheet	0.15	0.040	0.047	0.004		
Air	Steel pipe	50.0	0.022	0.026	2.273		
Insulation	Heat reflection	5.0	0.005	0.006	1.000		
Insulation	XPS foam board	100.0/100	0.023	0.027	4.348/4.348	0.082	0.096
Sheathing	Polyethylene sheet	0.15	0.040	0.047	0.004		
Interior surface heat resistance					0.127		
Total		255.3			12.154		

4. RESULTS AND DISCUSSION

4.1 Monitoring of indoor environments: temperature, humidity, and CO_2 concentrations

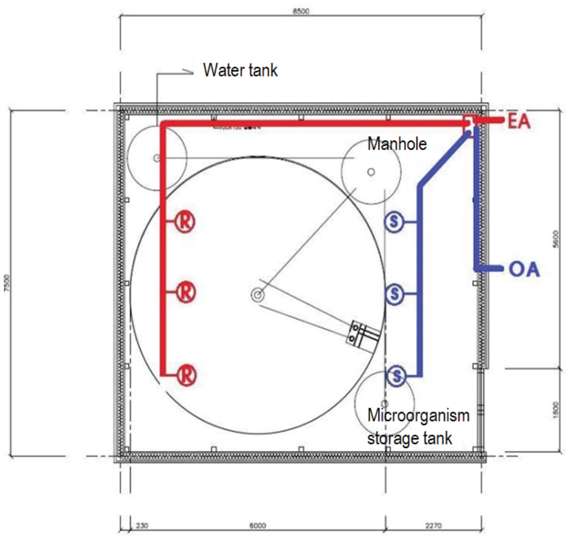
To evaluate each design's indoor environmental performance, primary indicators—including temperature, humidity, and CO_2 density—were monitored for approximately one year (2016–2017) during the hours of fish-farming operation. These indicators may not be critical for fish to grow, as air temperature and humidity do not significantly influence the fish-farming water cage environment. Consistent heat exchanges between the air and water in the houses are likely to cause the environments to vary to some degree; moreover, they affect the health of fish

FIGURE 4. Design 3: Construction details.

Wall-to-wall (horizontal): Average temp. 20.6!C Wall-to-roof (vertical): Average temp. 20.6!C

Simulation inputs - Temperature: 21 (indoor)/-10 (outdoor) !C; humidity (indoor): 50%

(a) Performance simulation for major building parts



(b) Mechanical ventilation: Air circulation route (EA: exhaust air for return; OA: outdoor air for supply)

farmers working in the houses. For the monitoring devices' sensors, we used Netamo® Weather Station as specified in Table 3.

4.1.1 Temperature variation

Monitored temperature profiles are presented in Figure 6 (a)–(d). During spring, the temperature variation was relatively more stable in Designs 2 and 3, whereas the baseline and Design 1 temperatures showed larger fluctuations ranging from 15°C to 30.6°C (22.2 ± 4.7°C) and 22.5°C to 32°C (26.8 ± 2.6°C), respectively (Figure 6 (a)). Note that the baseline temperature stayed much lower and wavering than the other designs' temperatures during March and April, demonstrating that the single-layer screen house is very prone to heat loss, especially when it gets closer to a cold season. Design 3, the Passive-design house, featured the most stable temperature profile all the way through the spring, while the peak temperature of Design 1 was 5–6°C higher than that of Design 3 in May. Compared to other seasons, temperature schedules in summer (Figure 6 (b)) are relatively more constant than in spring, hovering around 25–30°C. Among

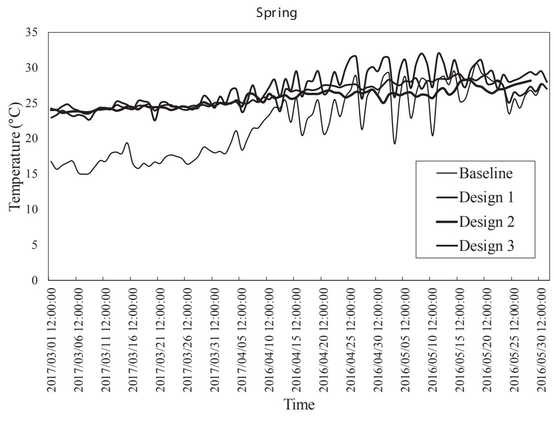
FIGURE 5. Construction of four test mock-ups (exterior and interior views).

these, the baseline temperatures peaked quite frequently. In August, baseline peaks were 2–6°C greater than those in other designs. Fall profiles are similar to those in the spring, if flipping in the right-left direction (Figure 6 (c)). As outdoor temperature decreases, all of the designs' interiors become cooler. Notably, Design 3 was far less influenced by cold temperatures, while the baseline temperatures plunged in October and November. Heat maintenance appeared to be similar in Designs 1 and 2 (Figure 6 (c)). Meanwhile, in Figure 6 (d), we identify a drastic temperature drop-off that occurred in the baseline. There are some ups and downs but the peak (January 8) is almost the same as the lowest point of Design 1. Temperatures in the winter, the coldest season in South Korea, demonstrate that existing fish-farming houses are very weak at cold perturbation. This finding indicates that houses' enclosures must be thermally reinforced against excessive heat loss. Otherwise, aquaculture will remain an energy-extravagant industry.

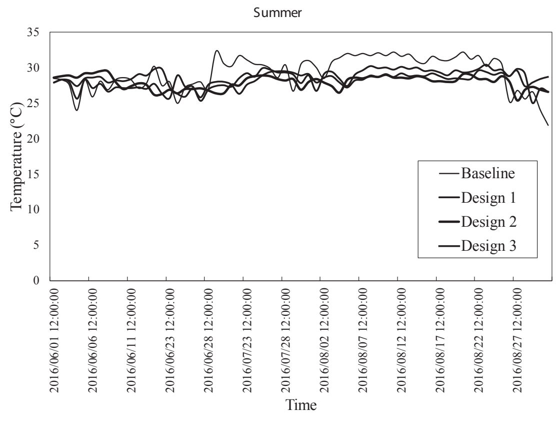
TABLE 3. Technical data of monitoring sensors (Netamo® Weather Station).

	Indoor	Outdoor
Size, mm	45x45x155	45x45x105
Temperature Range, °C Accuracy, °C	0–50 ±0.3	–40–65 ±0.3
Humidity Range, % Accuracy, %	0–100 ±3	0–100 ±3
CO_2 Range, ppm Accuracy, %	0–5,000 ±5	0–5,000 ±5

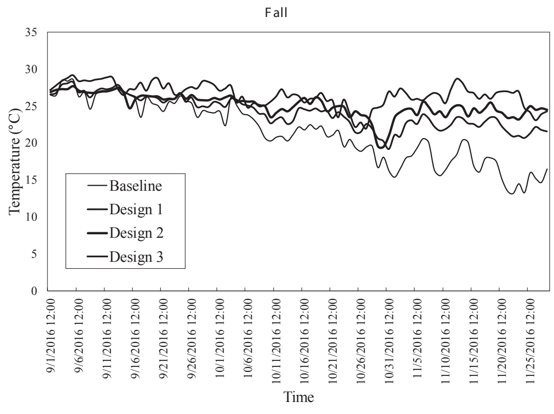
FIGURE 6. Indoor temperature variations.



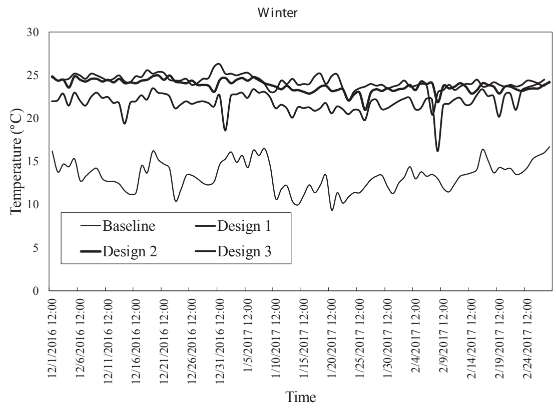
(a) spring



(b) summer



(c) fall

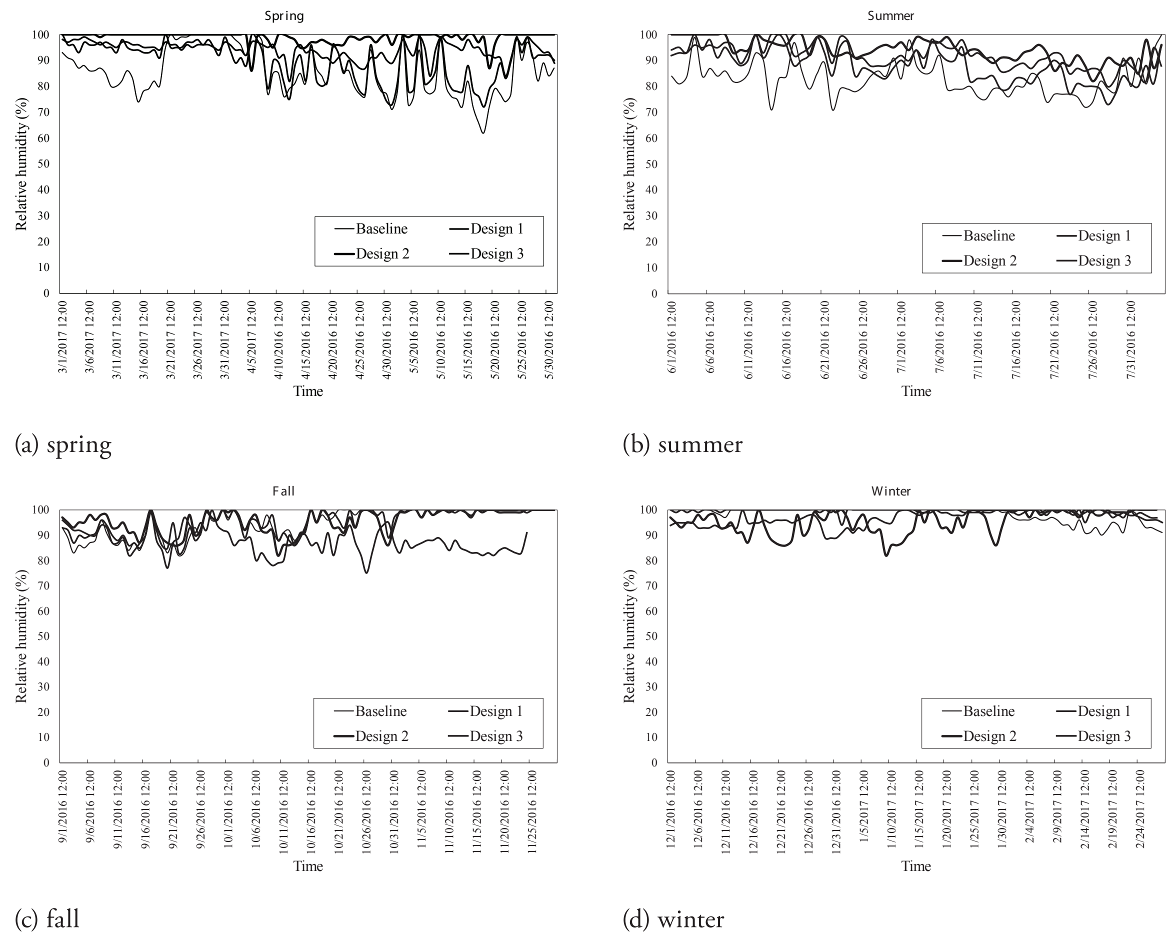


(d) winter

4.1.2. Humidity variation

Figure 6 presents the designs' monitored humidity levels by season. In general, humidity variation based on design was not greater than temperature. This is due to the water vapor that is produced from the cage and as farmers open doors while they work. Nevertheless, Design 2 showed greater humidity levels throughout all seasons except for winter (Figure 6), demonstrating its effectiveness to block off vapor. In winter, indoor humidity levels remain much higher than in other seasons (average 98.6%) because, in general, fenestration is closed all day. However, we identified that the Passive design's humidity was moderately lower and the air condition was better due to periodic mechanical ventilation to achieve air exchange with the ambient outside. Heat-recovery ventilation (HRV) devices were installed to offset heat loss. Comparing this result with the temperature levels (Figure 6 (d)), we expect the thermal resistance of Design 3 to be slightly greater than that of Design 2 (although the two temperature profiles appear similar), despite forced air infiltration in the winter.

FIGURE 7. Indoor humidity levels.



(a) spring

(b) summer

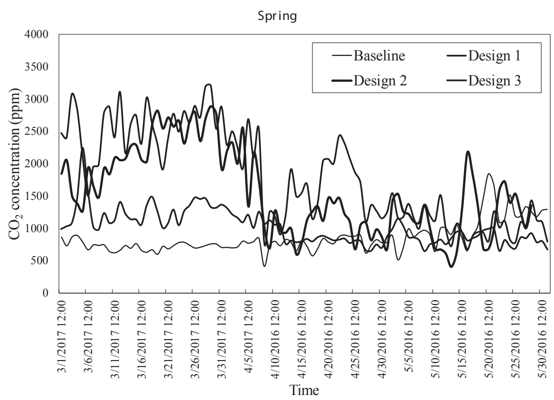
(c) fall

(d) winter

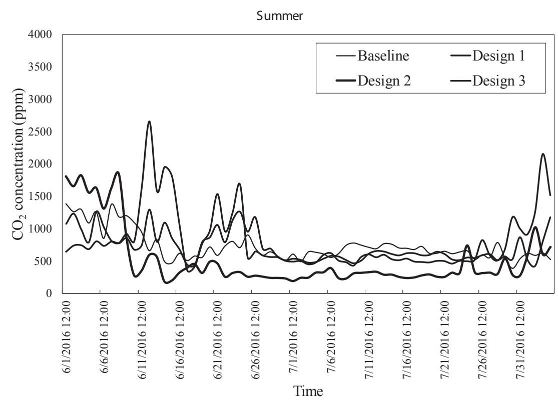
4.1.3 Indoor CO_2 concentrations

Typical levels of CO_2 concentrations in occupied indoor spaces range from 350 to 1,000 ppm (Persily and de Jonge, 2017). The workplace exposure limit of CO_2 in a room (for eight hours of work per day) is 5,000 ppm, but it is reported that high concentrations of CO_2 (greater than 2,000 ppm) and stale air may cause serious oxygen deprivation, headaches, loss of attention, and even brain damage. To determine each design's enclosure performance, we measured indoor CO_2 concentrations in spring and winter. Monitoring during the summer was not considered, as the houses operate all the fenestration open to the outside. In spring, the CO_2 profiles of Designs 1 and 2 tended to fluctuate largely (σ = 740, 662 ppm) (Figure 8 (a)), showing greater CO_2 levels despite intermittent, sharp drop-offs. Note that CO_2 levels in Design 1, in particular, reached up to 3,206 ppm, while Design 3 mostly maintained appropriate levels between 500 and 1,500 ppm (average 1,012.5 ppm). For the purposes of this study, we ignored an odd-looking sharp rise on Mar. 5th by considering it an outlier point. As shown in Figure 8 (b), Design 3 showed greater CO_2 concentrations in summer (average 845.9 ppm; max 2,656 ppm) than in spring. However, in summer, by the same token as humidity, overall lower CO_2 reveals

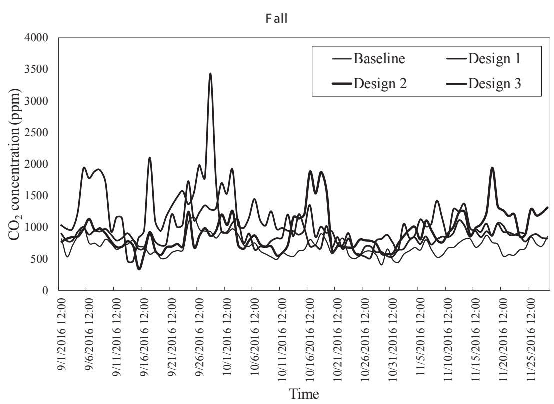
FIGURE 8. Monitoring results of indoor CO_2 levels.



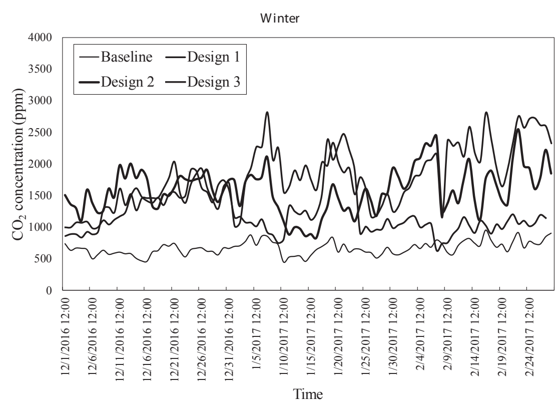
(a) spring



(b) summer



(c) fall



(d) winter

that chemical compounds in the air are not significant for indoor health. Although Design 3 peaked at 3,429 ppm, the air quality in the fall (average 911.6 ppm) was as fine as in summer (Figure 8 (c)). Meanwhile, CO_2 became increasingly concentrated during early spring and winter, when the air was heated. This indicates that the heat exchanger installed in the Passive house underperformed on freshening the air in the room.

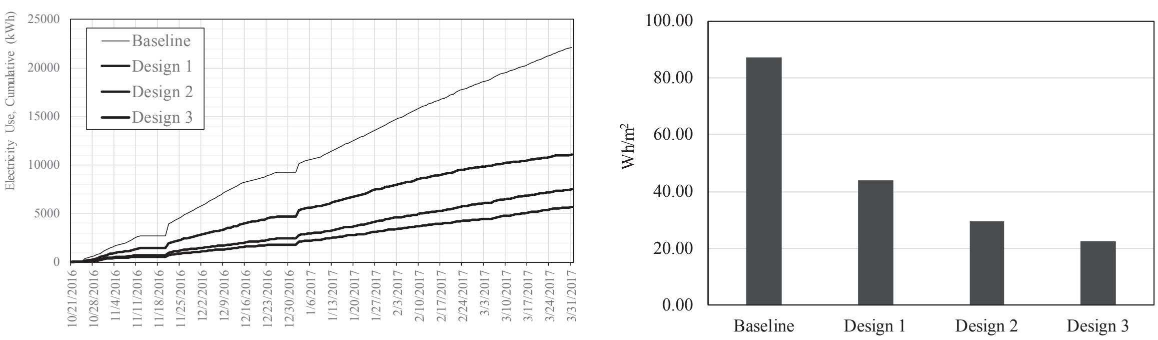
4.2 Energy use meter data

In general, eel-farming systems consume vast amounts of energy to keep the water warm, as eels are very sensitive to farming environments and the ideal temperature range of the eel-growing water is 23~28°C (Banrie, 2013) (water temperatures outside the ideal range will result in decreased growth rates and biological stress). We collected meter data of electricity end-use during operation hours to determine each design's energy performance. Electricity throughputs for fish-farming houses are twofold: (i) for water cages and (ii) for buildings. Terminal devices in water-cage electricity include water heaters, air blowers (motors + fans) for water treatment, and dissolvers. Electricity for lighting fixtures and HRV devices are classified in building use. The greatest amount of energy is expected to be consumed during the winter season to keep the water temperatures in the ideal range. Hence, we monitored electricity meters from Oct. 21th, 2016 to Mar. 31th, 2017 (162 days).

4.2.1 Energy use for water heaters

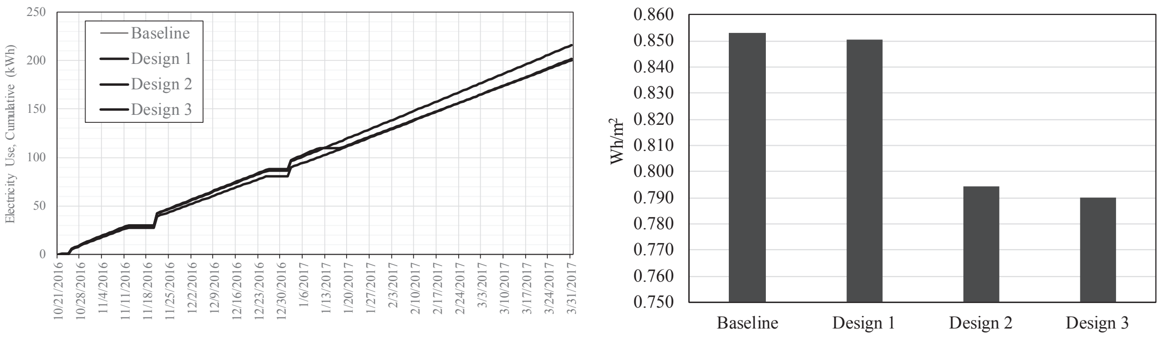
During the observation period, electricity use for water-cage heating varied largely according to the performance of alternatives; the baseline consumed the most energy (87.15Wh/m^2) while Design 3 used only 22.49Wh/m^2 (Figure 9). Compared to the baseline, Design 1 reduced electricity use by 49.72%, Design 2 by 65.88 %, and Design 3 by 74.19% (Figure 9 (b)). In terms of cage warming, the plastic screens (baseline and Design 1) can benefit from easily induced solar heat; inversely, the screens' high conductivity makes them prone to overnight heat loss, which results in greater energy use than other alternatives. This reveals that the enclosures' thermal insulation and air tightness are critical to saving some of the operational energy of fish-farming houses.

FIGURE 9. Water heater energy consumption (10.21.2016 ~3.31.2017).



(a) Cumulative energy consumption (b) Comparison of energy use intensity

FIGURE 10. Blower energy consumption (10.21.2016 ~3.31.2017).



(a) Cumulative energy consumption

(b) Comparison of energy use intensity

4.2.2 Energy use for air blowers

Figure 10 shows that air blowers are not dominant energy consumers since they use much less electricity than water heaters (less than 250 kWh). Even if the blowers in Designs 2 and 3 used lesser amounts, 0.79 Wh/m^2, there was only a slight difference (0.06 Wh/m^2).

4.2.3 Energy use for dissolvers

In intensive aquaculture, oxygen dissolvers are installed to artificially increase the concentration of gaseous oxygen (O_2) in the water. Through forced infusion using air circulation pumps, oxygen is mixed into the water. Figure 11 shows that dissolvers consumed vast amounts of energy (4,500 ~ 5,000 kWh per house), yet there were relatively minor differences among the designs. Contrary to the study's results for heaters and blowers, Design 3 operated the dissolvers with the highest electricity use of 19.76 Wh/m^2.

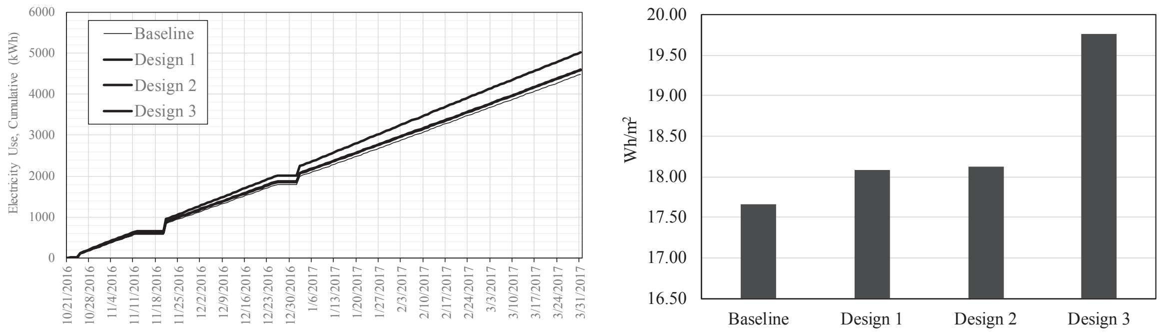
4.2.4 Energy use for lighting and HRV

Figure 12 (a) reveals that lighting demands much fewer electricity inputs than other devices. Designs 1 and 2 consumed around 14 kWh for lighting (0.056 Wh/m^2 and 0.057 Wh/m^2). Design 3 reduced this by 32%; however, the reduced quantity is so small (0.017~0.018 Wh/m^2) that it can be ignored. HRV was only used in Design 3. During the monitoring period, it used up to 390 kWh (1.53 Wh/m^2) of electricity.

4.2.5 Total energy use

Aggregated meter data were used to draw comparisons. Table 4 and Figure 13 clarify that the current design of fish-farming houses wastes energy. While the baseline consumed 105.71 W/m^2/h, Design 3 used only 40.60 Wh/m^2 (–57.8% savings), Design 2 used 48.71 Wh/m^2 (–53.92% savings), and Design 1 used 62.80 Wh/m^2 (–40.59% savings). In Figure 13 (a) and (b), the baseline is shown to consume electricity one and a half to two times greater. The baseline operated with 27 MWh (105.7 Wh/m^2) during the study period while the other designs used less than 16 MWh. On the other hand, it can be seen that electricity for water heaters and dissolvers dominates aquaculture's end-energy use; HRV, blowers, and lighting take on minor

FIGURE 11. Dissolver energy consumption (10.21.2016 ~3.31.2017).

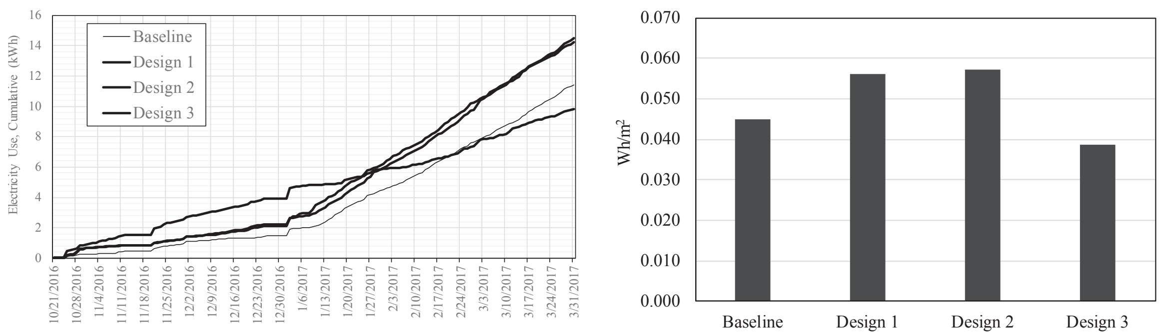


(a) Cumulative energy consumption

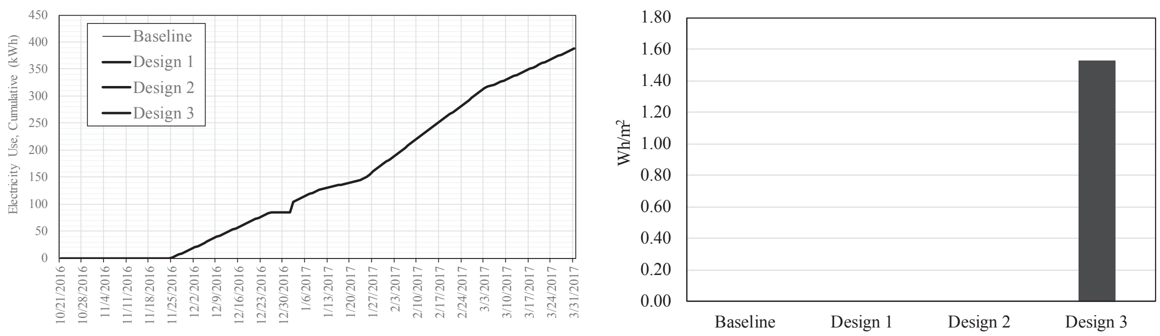
(b) Comparison of energy use intensity

roles. Energy use for dissolvers is a large concern (19Wh/m^2), so energy-efficient dissolvers must be considered to lower total energy quantity (Figure 13 (c)). That said, since dissolvers are not dependent on building design (Figure 11), we suggest that reducing water heaters' energy use is critical to saving building energy in terms of fabrication (Figure 13 (c)). To do so, it is necessary to maximize the efficiency and performance of thermal transport through the building envelope.

FIGURE 12. Energy consumption of lighting and HRV.



(a) Lighting cumulative energy use (left) and comparison of energy use intensity by design

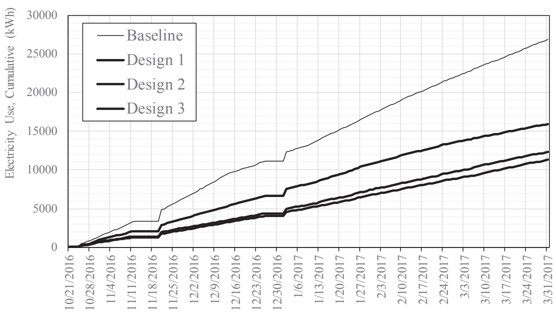


(b) HRV cumulative energy use (left) and comparison of energy use intensity by design

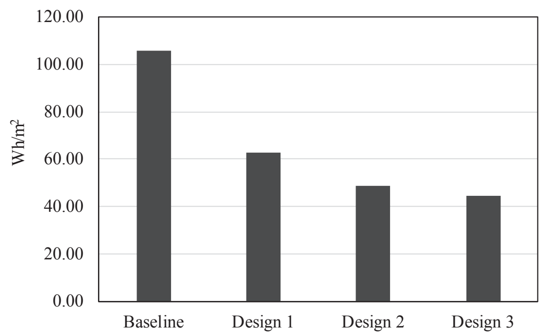
TABLE 4. Total energy consumption comparison.

Items	Baseline	Design 1	Design 2	Design 3
Total Energy Consumption, kWh	26,817	15,933	12,357	11,315
Area, m^2	65.25	65.25	65.25	65.25
Use per day, kWh/day	165.54	98.35	76.28	69.85
Use per hour, kWh	6.90	4.10	3.18	2.91
Use per hour per area, Wh/m^2	105.71	62.80	48.71	44.60
Energy saving ratio, %	—	–40.59	–53.92	–57.81

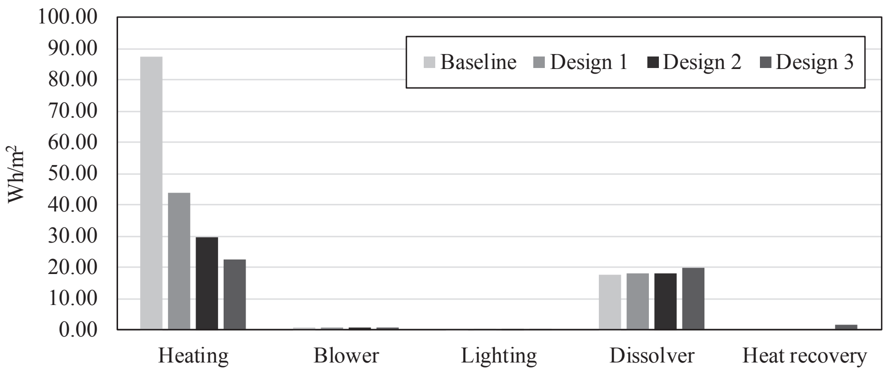
FIGURE 13. Total energy use.



(a) Cumulated total energy consumption



(b) Total energy use intensity by design



(c) End-energy use breakdown by component

4.3 DISCUSSION AND COST ANALYSIS

4.3.1 Strengths and weaknesses of the design alternatives

This study found that the baseline, a general translucent single-layer plastic house, has advantages in terms of maintaining higher air quality. However, this results from poor fabrication and air infiltration through the plastic screen; therefore, excessive heat loss associated with air leakage and highly-conductive metal framing leads to suboptimal energy disposal. As identified in the performance of Design 1, threefold plastic screening can increase energy efficiency (40%), taking advantage of indoor daylight availability and solar heat absorption. In Design 2, enclosing with vault-structured insulation materials appears useful in maintaining stable indoor temperatures, in addition to saving electricity use for cage heaters and blowers. Enhanced enclosure fabrication, however, leads to an increase in indoor CO_2 concentrations. Design 3, the Passive house, features the most stable temperature variations throughout building operation hours. Design 3 is characterized by a high degree of thermal insulation and air-tight envelopes that are beneficial in reducing energy. In addition to these factors, Design 3 also demonstrates that the use of HRV equipment helps to maintain CO_2 concentrations at a suitable level while keeping the air warm. These findings comprehensively indicate that the Passive-house design outperforms other methods with the greatest potential for energy saving and effective maintenance of a healthy indoor environment.

4.3.2 Examination of cost-effectiveness

Beyond energy-saving issues, cost-benefit is another important factor in the feasibility of alternative house designs. The comparative cost estimates of the mock-up constructions (Table 5) show that building manufacturing is the primary difference in terms of total construction costs, while expenses for equipment (water cages, mechanical facilities, etc.) are identical. The construction cost of Design 2 is higher by 135.8%. Even if Design 2 can manage to reduce operation costs, the payback period is 35.3 years due to the immoderate cost of house manufacturing. Design 1 is the most cost-effective alternative, saving energy use with relatively cheaper materials and

TABLE 5. Expenses for mock-up constructions.

Expenses	Baseline	Design 1	Design 2	Design 3
Building manufacturing (*A*, KRW)	6,359,740	9,590,820	27,334,000	17,783,320
Equipment (*B*, KRW)	9,084,802	9,084,802	9,084,802	9,084,802
Sum (*A*+*B*, KRW)	15,444,542	18,675,622	36,418,802	26,868,122
Extra construction cost (KRW)	0	3,231,080	20,974,260	11,423,580
Construction cost increase (%)	—	20.9	135.8	73.9
Electricity use (kW)	26,817	15,933	12,357	11,315
Electricity saving (KRW)	0	-446,244	-592,860	-635,582
Payback period (year)	—	7.2	35.3	17.9

Note: 1 KRW ≈ 9.5E-4 USD

lightweight construction. Design 1's reduced electricity is smaller than the other two alternatives, yet it takes only 7.2 years to recoup initial investment costs. Design 3 has the greatest energy-saving potential (57.81%, Table 4), but its increased inputs for complex construction (including labor and materials) result in a payback period much longer than that of Design 1 (17.9 years).

5. CONCLUSIONS

Given the broad scope of the energy use of the South Korea's marine sector, it is important to address the environmental sustainability of aquaculture. The poor design and crudely-assembled construction of fishery facilities significantly hinder the development of an energy-efficient and cost-effective marine industry. In an effort to reduce the energy use of South Korea's local pisciculture, this study focused on the environmental improvement of existing fish-farming buildings. The present single-layer plastic screen houses are a primary cause of energy waste and excessive costs in the operation of aquaculture. We attempted to reduce operational building energy by suggesting and mocking up alternative advanced designs of fish-farming houses. By introducing environmental building techniques aligned with locally available materials and construction methods, this study offered three alternative designs (Designs 1, 2, and 3). The results of field experiments to examine the performance of the study's test buildings are summarized as follows. (1) Designs 2 and 3 are superior in retaining indoor warm air in winter; temperatures in Design 1 fluctuate largely between day and night, but owing to the introduction of solar heat, daytime ranges were not extremely detrimental to fish growth; indoor humidity levels in winter appear very high for all designs, but they do not negatively influence the indoor environment; although CO_2 concentrations often reach over 3,000 ppm, they do not have an impact on workers' health; and lower CO_2 levels in Design 3 are a result of the operation of HRV. (2) Monitored meter data showed that Passive-house construction (Design 3) can reduce energy the most by 57.8% compared to the baseline, while Designs 1 and 2 feature reductions of 40.59% and 53.92%, respectively. (3) Total construction costs are highest for Design 2 (2.48 times as expensive as the baseline), which was constructed out of high-density insulation materials and required significant skilled manpower to finish building surfaces. For the manufacturing of Design 3, the costs were 1.55 times higher than for the baseline. (4) Considering trade-offs with energy reductions in operation, Design 1 has the greatest cost-benefit. We expect that it will take only 7.2 years to recoup initial costs with Design 1, while Designs 2 and 3 will take approximately 35.3 and 17.9 years, respectively. Therefore, Design 2 is an undesirable alternative, but if we estimate a 20-year lifespan for fish-farming houses, Design 3 could become a strong candidate to replace existing houses.

The study's findings demonstrate that thermal reinforcement on the building skin—by either switching materials or changing the fabrication—is conducive to improving energy use as well as indoor environment. This study immediately contributes to the practice of aquaculture, particularly in the case of farming temperature-sensitive fish. Stakeholders involved in fish farms (workers, landowners, construction contractors, etc.) and, more broadly, policymakers in the areas of fisheries and industrial energy use will benefit from this study, as it can help them make effective decisions and take appropriate actions to pursue the sustainability of the ocean and fish industries. Further research will be conducted to suggest improved options and a novel type of fish farm design, integrating the merits found in the present study's building designs.

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