Article

Optimization of a Wood Pellet Boiler System Combined with CO₂HPs in a Cold Climate Area in Japan

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Abstract: Hot water supply is one of the leading consumers of energy in the building sector in cold climate areas. The use of woody biomass is effective in reducing CO₂ emissions in hot-water supply systems. This report deals with a system that combines a wood pellet boiler (PB) and a heat pump system with CO₂ (CO₂HP) that is used in a facility for disabled people. The following research was conducted. The operation of a hybrid system combining a PB and CO₂HPs was investigated. While operating the system, four specific operations were developed as countermeasures to save on costs and reduce system troubles while reducing CO₂ emissions. The processes and results are introduced. Numerical simulations were carried out to optimize the operation. The hot water temperature, water volume, and hot water loads were simulated. The influence of the water volume ratio on the cost and primary energy consumption under the requirements for safe system operation was studied. The regional economic ripple effects (REREs) of this system were studied. The wood pellet boiler is not only a measure for reducing primary energy consumption but can also play an important role in a regional economy for sustainable development in countries that import energy resources such as Japan.

Keywords: woody biomass; wood pellet boiler; heat pump; combined system; hot water supply; regional economic ripple effect

1. Introduction

The building sector contributed over 35% of final energy use in the European Union (EU) in 2016 [1]. In recent years, there has been a need to reduce the operational energy of buildings due to concerns about global warming and environmental pollution. Hot water supply is one of the leading consumers of energy in buildings in cold climate areas [2], and energy-saving for these systems has a great impact on reducing energy consumption and CO₂ emissions in the building sector.

The use of woody biomass is effective in reducing CO₂ emissions in hot-water supply systems with wood pellet boilers (PBs). Woody biomass has a small heat content compared with that of fossil fuels, but it achieves carbon capture through harvesting and planting. Woody biomass is a very effective way to achieve zero emissions [3]. However, because the amount of carbon storage in forests varies depending on the type of building and system [4], external effects, such as the effects of environmental pollution on the environment, also need to be considered [5]. Woody biomass is widely used, especially in Europe, and there are many studies on its current status and standards [6,7]. Japan, the target of this report, is one of the world's wealthiest countries in terms of forest resources.

In addition, biomass is a useful energy source for the future due to the lack of other fossil fuels in Japan. However, the forestry industry in Japan has been decimated by price competition. As a result, woody biomass fuels are produced by companies that are financially unstable, and the disadvantages of the fuels are their relatively high cost and lack of stable supply. Thus, the production of woody biomass fuel can stabilize their management. The use of woody biomass fuel can not only reduce CO₂ emissions but also revitalize the forest industry, prevent disasters caused by forest degradation, and promote the local economy.

The solution to a stable supply of energy for supplying hot water is to use an electric system. Electricity has a large primary energy consumption coefficient in Japan, but the disadvantage can be mitigated using heat pumps. In Japan, a heat-pump system called the “CO₂HP” that uses CO₂ as a refrigerant is widely used. Its development and adoption have been rapid because of its high efficiency when outdoor temperatures are high and because of its cost advantages when used with a water storage tank. Since the Great East Japan Earthquake in March 2011, there have been concerns about the future of electric power systems in Japan. However, areas where gas is cheap are rare, and the introduction of renewable energy is progressing gradually; thus, the share of CO₂HPs is expected to increase in the future. The JRAIA (Japan Refrigeration and Air Conditioning Industry Association) published a document on the CO₂HP in 2020 [8]. The document reports that CO₂HP sales since 2001 exceeded 7 million units in June 2020. The top reasons for consumer purchases were cost benefits, all-electric housing, and fire protection. In addition, in Japan, feed in tariff (FIT) is applied to PV systems for 20 years, and electric power companies are not obligated to purchase electricity generated by PV systems after 20 years. CO₂HPs are expected to be used as a destination for electricity from expired PV systems [9].

However, the heating capacity of CO₂HPs is not high enough per unit. Therefore, in some cases, it is difficult to cover the entire hot water supply load with CO₂HPs due to the installation space and initial cost. Additionally, in Japan, where fossil fuels are currently relied on to generate electricity, the electric system has a relatively high primary-energy conversion coefficient. A hybrid water heating system combined with other combustion water heating systems eliminates these shortcomings. Hybrid solar and biomass boiler systems were dealt with in [10–12]; however, while high efficiency and reduced CO₂ were reported, there were only examples of small-scale systems [13]. The hybrid water heating system in this report combines CO₂HPs and a wood pellet boiler. The system has the potential to reduce CO₂, operate stably, and provide cost benefits at the same time in Japan, but there is little expertise on how to operate the system. Mori et al. reported on the initial operation and found that although the operation cost increased, the use of wood pellets during the daytime significantly reduce CO₂ emissions [14]. On the other hand, the impact of high operational costs on the local economy was not analyzed. In this report, information on the features and the improvements of this system are summarized. Additionally, numerical calculations are carried out to analyze the operation with the safety operation, cost, CO₂ emission, and the regional economic ripple effect. The following is a summary of the work in this report.

1. The operation of a hybrid system combining a PB and CO₂HPs was investigated. While operating the system, four specific operations were developed as countermeasures to save on costs and reduce system troubles while reducing CO₂. The processes and results are introduced.
2. A numerical simulation was carried out to optimize the operation. The hot water temperature, water volume, and hot water loads were simulated. The influence of the water volume ratio on the cost and primary energy consumption under the requirements for safe system operation was studied.
3. The regional economic ripple effects of this system were studied. The wood pellet boiler is not only a measure for reducing the primary energy consumption but can also play an important role in a regional economy for sustainable development in countries that import energy resources such as Japan. Using regional economic input-output tables (I/O table), the influence of wood resources for wood pellets on regional economic ripple effects are introduced.

2. Improvements to Operation

2.1. Facility and Hot Water System

Figure 1 shows a picture of a facility. This facility is a multifunctional welfare facility with a total floor area of 8000 m², located in Date City, Hokkaido, Japan. About 150 people, who are intellectually challenged, use the facility. It provides support for daily life and educational activities aimed at self-support. The stable hot water supply, which is used for cooking, washing dishes, and bathing, is important for the facility.

Figure 1. Picture of the facility.

Figure 2 shows a schematic diagram of the hot water supply system, in which a PB (290 kW, stoker-fired type) and CO₂HPs (50 kW × 3 units) were installed in parallel with a 20 m³ hot-water storage tank. The tank accepts hot water from different types of heat sources. The purpose of this system is to ensure the stable combustion of woody biomass boilers in order to avoid dirty emissions [15]. Additionally, the storage tank helps to achieve highly efficient operation by taking advantage of the PB and CO₂HPs. The CO₂HPs have two circuits. One is a storage tank circulation circuit (STCC), which reheats the hot water in the storage tank. The other is a well water heating circuit (WWHC), which heats well water and supplies it to the storage tank. The WWHC is more efficient because it can increase the coefficient of performance (COP) with a wider temperature difference; according to the specifications, the winter efficiency (7 °C) is 3.61 for the WWHC and 1.34 for the STCC. In the original operation (Operation A), the priority of the PB is on reducing CO₂ emissions. When the PB heating rate is inadequate, the CO₂HP is operated using STCC when the hot-water storage tank is full. Otherwise, the CO₂HP is operated with the WHCC when the hot-water storage tank is not full.

2.2. Summary of Energy to Operate Facility and Hot Water System

Figure 3 shows the primary energy consumption of the facility for one year after completion. The primary energy consumed by the CO₂HPs and PB together accounted for 6% when the primary energy was calculated to be 9.76 MJ/kWh for the CO₂HPs and 0.72 MJ/kWh for the PB. The primary energy increased to 15% when 3.6 MJ/kWh was used as the transformation coefficient for the PB. In other words, the PB significantly reduced the primary energy.

Figure 2. Hot-water supply system.

Figure 3. Primary energy consumption. PB: wood pellet boiler; AC: Air conditioner

Figure 4 shows the total electric power in the building during the peak season. The peak power was reached in the afternoon of the 2nd of March. The facility supplied hot water to the bathtubs and showers as well as for cleaning and cooking simultaneously. Figure 5 shows a boxplot of the hot water demand per hour. The peak hour was 2 p.m., when all activities requiring hot water supply were conducted. The demand increased the peak electric power by 40 kW. In Japan, the electricity bill increases by 1 million yen (9500 dollars) per year due to a peak increase in the electric tariff system.

Figure 6 shows the system COP calculated by the energy consumption and generated hot water of the CO₂HPs when the CO₂HPs were operated with the STCC. The median COP was decreased when the outside temperature was under 5 °C. Additionally, the COP was smaller than 1.0 when the outside temperature was under 0 °C. The reason for the low COP was an electric heater, which turns on as an anti-freezing measure when the temperature is under 5 °C. The STCC caused a lower COP than the WWHC, which heats cold well water. The target facility is located in a cold climate area, thus, the system operation needed to be improved.

Figure 4. Electric power during peak season.

Figure 5. Box plot of hot water supply demand.

Figure 6. System coefficient of performance (COP) of the CO₂HPs.

2.3. Improving Operation of Hot Water System

This complex system consists of CO₂HPs, a PB, and a hot-water storage tank. Each operates independently and has its own systems to improve efficiency and safety. Therefore, it is difficult to predict the system's influence on other systems in advance using a system simulation. Therefore,

the optimal operation of the system was studied while the system was operated. An overview of the operation is shown in Table 1. The purpose of the optimization is to reduce costs and CO₂ by taking advantage of the advantages of composite systems. Because this system includes a PB, CO₂ is automatically reduced. Therefore, the main topic of this study was the efficient operation of the CO₂HPs. Additionally, the system was in actual operation, thus, system failures, such as hot water shortages and low hot-water supply temperatures, needed to be avoided as much as possible.

Table 1. Summary of the operation.

Operation	PB	CO ₂ HP	Hot Water Storage
		CO ₂ HPs were used as secondary system for PB.	
Operation A	The operation of PB always had priority. Operation started at 6. a.m. and stopped at 9 p.m.	CO ₂ HPs supplied hot water when water level in hot-water storage tank dropped with well water heating circuit (WWHC) and load could not be covered by PB alone with storage tank circulation circuit (STCC).	Volume was controlled to full. Water supply rate was high (about 200 L/min).
Operation B	The operation started at 6. a.m. and stopped at 7 p.m.	System started at 9 p.m. and stopped at 6 a.m. CO ₂ HPs supplied hot water with STCC.	Volume was controlled to full. Water supply rate was high (about 200 L/min).
Operation C	Operation started at 6. a.m. and stopped at 7 p.m. Anti-freeze operation started.	System started at 9 p.m. and stopped at 6 a.m. CO ₂ HP supplied hot water with STCC.	Volume was controlled to full. Water supply rate was half to avoid drop in hot water temperature.
Operation D	Operation started at 6. a.m. and stopped at 7 p.m.	System started at 9 p.m. and stopped at 6 a.m. CO ₂ HPs supplied hot water with WWHC at night.	Volume was controlled to full at night and half during day.

Figures 7–9 show the improvement to the actual operation of the system. Figure 7 is the original operation (Operation A). Here, the operation of the PB had priority during the daytime. The CO₂HPs operated with the WWHC at the peak to supply hot water to the storage tank. Additionally, the operation of the CO₂HPs was scheduled to maintain the temperature during the night to keep the electricity cheap as a cost merit. However, the CO₂HPs did not operate during the night because there was no hot water demand during the nights at the facility. Then, the operation of the PB was terminated at 7 p.m. to decrease the wood pellet consumption and stop the operation of the CO₂HPs during the daytime to decrease the peak electric power generated with the CO₂HPs in Operation B. The CO₂HPs were operated with the STCC in the early morning, and the PB was stopped at 7 p.m. as shown in Figure 8. The operation decreased the peak electric power by 33 kW at 3 p.m. on the 13th of June and reduced the heating energy generated with the PB from 134 GJ/month in June to 129 GJ/month in October. Additionally, the primary energy for hot water supply decreased from 76 GJ to 52 GJ because of the reduction in wood pellet consumption. Operation B continued to perform very well during the summer season. However, the hot water temperature did not rise sufficiently due to the low outside air temperature and low water-supply temperature. The PB had a sufficient enough capacity at the catalog value (290 kW), but the local wood pellets did not have a sufficient enough calorific value. EU countries have standards for wooden fuel pellets [16,17]; however, in Japan, there are no standards for the quality of wood pellets, thus, the calorific value of the pellets varies greatly depending on the plant and the resource. M.Y. Haller described the same situation [18]. The pellet plant located in Date City plays an essential role in the promotion of local forestry and forest conservation. Additionally, the pellets are bulkier than other fossil fuels. Considering that the cost and CO₂ emissions for transportation reduce the benefits of wood pellets, it is necessary to continue using pellets from this plant [19,20]. Thus, improvements to the operation were made again. In general, when an open-type hot water storage tank is used, the water level is controlled to about full to prevent air entrainment. However, when the supply water temperature to the tank is low, the large amount of cold supply water causes the hot water

heating load to be huge. The size of the hot water storage tank was enough for the hot water supply. Thus, the well water supply rate to the tank was reduced to reduce the peak heating rate. Figure 9 shows the heating rate and hot water temperature for Operation C. The hot water temperatures were stable at around 70 °C. Since the well water supply rate was decreased, the hot water temperature in the storage tank dropped slowly, and the PB was able to control the hot water temperature. However, the operation caused a drop in the water level to about half. This operation reduced the primary energy consumption from 52 GJ/month in October to 39 GJ in December while keeping the water temperature hot. The hot water energy of the PB increased from 129 GJ in October to 152 GJ in December. A problem during that period was the suspension of CO₂HP operation. In the winter season, the PB operates intermittently, even at night, for anti-freezing. Since the heat caused by the operation maintained the temperature in the hot water storage tank, the CO₂HPs lost the opportunity to operate. Figure 10 shows the current operation (Operation D). The water control level in the hot water storage tank is lowered during the daytime and is full during the night after 9 p.m. The CO₂HPs supply hot water to the tank with the WWHC, which leads to high energy efficiency with cheap electricity at night.

Figure 7. Results of Operation A.

Figure 8. Results of Operation B.

Figure 9. Results of Operation C.

Figure 10. Current operation (Operation D).

3. Numerical Simulation of Hot Water Supply

3.1. Summary of Simulation

The flow and heat balances of the system were simulated to analyze the effects of cost and CO₂ emission reduction and the regional economic ripple effect (RERE) for Operation D. There is much research on optimizing hot water supply systems with numerical simulation [21]. However, there are few pieces of research on improving the operation of existing systems in terms of cost, primary energy, and the economic ripple effect, as in this study.

Figure 11 shows a schematic diagram of the simulation. The heat and water flow from the CO₂HP with WWHC and STCC were considered as well as the well water supply, the PB, and the heat loss from the storage tank to calculate the hot water temperature and the volume of the storage tank. The measurement data from the 26th of September to the 10th of October 2012 were used as the demand for the hot water supply every 10 min. The time interval of the calculation was also 10 min. A flowchart of the analysis is shown on the right side of the figure.

The analysis was conducted by coding, not by software. First, initial conditions such as the amount of hot water, hot water temperature, and the upper limit of the hot water storage tank were set, and hot water and well water supply to the hot-water storage tank were then determined on the basis of the hot water demand. Then, the volume of hot water was calculated using Equation (1), and the temperature of the hot-water storage tank was calculated using Equation (2). If the respective heating loads exceeded the heating capacities, the drop in hot water temperature was calculated by convergence calculations. This procedure was performed for a series of hot water loads. The flow balance equation includes the volume of the hot water storage tank (V_T), the feedwater from the

well (q_{WS}), the CO₂HP feedwater with WWHC (q_{HP}), and the hot water supply (q_{hs}) as shown in Equation (1):

$$\frac{dV_T}{dt} = q_{WS} + q_{HP} - q_{hs} \quad (1)$$

where q_{WS} represents the well water supply, which is defined as a constant value at the initial stage and q_{HP} is the feedwater rate with the CO₂HP (30.6 L/min). These water supplies are stopped when the hot water volume reaches a defined level. The heat balance equation for calculating the temperature in the hot-water storage tank (θ_T) considers the heat with the well water inlet, the heating rate with the CO₂HP, the heating rate with the PB, and the heat loss from the hot-water storage tank, as shown in Equation (2):

$$c\rho V_T \frac{d\theta_T}{dt} = c\rho q_{WS}(\theta_{WS} - \theta_T) + c\rho q_{HP}(\theta_{HP} - \theta_T) + c\rho q_{PB}(\theta_{PB} - \theta_T) + US(\theta_O - \theta_T) \quad (2)$$

where θ_{WS} represents the well water temperature, which is always 10 °C based on the winter data, and θ_{HP} and θ_{PB} stand for the feedwater temperature of the CO₂HP and PB, respectively. Usually, θ_{HP} is 65 °C and θ_{PB} is 70 °C, but these temperatures are re-calculated when the heat calculated with $c\rho q_{HP}(\theta_{HP} - \theta_T)$ and $c\rho q_{PB}(\theta_{PB} - \theta_T)$ is over the heating capacities of the CO₂HP and PB. The capacities were 166 kW for the PB and 150 kW for the CO₂HP. θ_O , which represents a surrounding temperature of the hot water storage tank, is always 20 °C. The thermal transmissivity of the wall to calculate the heat loss from the hot-water storage tank is defined as U (0.38 W/m²K). S , which stands for the heat-loss area, considers the wet-surface calculated by the hot water volume and the size of the storage tank (3 m × 3 m × 3 m).

Figure 11. Schematic diagram of simulation.

3.2. Simulation Results

Figure 12 shows the calculation results for the water volume and hot water temperature in the storage tank for Operations B, C, and D. The water storage was maintained at almost full in Operation B, which has a high supply water rate. For Operations C and D, the water volumes were low on bathing days when the supply water rates were decreased. The difference between C and D is the definition of the hot water control volume during the daytime. In the case below, the volume was set at 12 m³. The volume decreased after 8 a.m. regardless of the hot water supply load, and the water supply was implemented to maintain the volume. The calculated temperature changes for operation B was in good agreement with the measured data shown in Figure 7. The hot water temperature dropped under 50 °C on bathing days on the 1st, 2nd, 3rd, and 5th of October for Operation B. However, the temperature in

daytime stayed over 65 °C for Operation C. For D, the temperature dropped again because the water volume was small. The balance between the water volume and the well water supply rate should be taken into consideration.

Figure 12. Calculated hot water volume and temperature.

Figure 13 shows the heating rate for C and D. The calculated changes in heating load for C did not agree well with the measured data in Figure 9 because the calculation did not take into account the anti-freeze operation during nighttime. Operation D, which lowers the daytime water volume, decreased the heating rate of the PB in the morning but increased the heating rate of the CO₂HP at night. It indicates that the operation successfully shifted the hot water supply load in the morning to the night. This shift is popular in Japan because electricity costs can be reduced. However, the primary energy consumption increased from 2.7 GJ/day to 5.7 GJ/day due to the increased use of electricity.

Figure 13. Heating rates of PB and CO₂HP in operations C and D. (a) Heating rate for Operation C. Well water supply rate = 50 L/min. (b) Heating rate for Operation D. Well water supply rate = 50 L/min. Daytime water volume = 12 m³.

3.3. Optimization of Operation

To investigate the relationship between cost and primary energy consumption, a parametric study was conducted. The parameters were the night water volume, the day water volume, and the well water supply rate. First, the night water volume was calculated with a random number in the range of 15–25 m³, and the daytime water volume was calculated by multiplying the night water volume with the rate generated by a random number from 0 to 1. The water supply rate was also generated with

a random number in the range of 0–250 L/min. The water volumes and the hot water temperatures were calculated for 2000 cases. Thirty-one cases that met the following requirements were included in the study. The requirements were that the lowest water volume was over 2 m³ and that the lowest hot-water temperature was above 50 °C.

Figure 14 shows the water supply rates that met these requirements in ascending order. The upper limit was 59 L/min because of the low hot-water temperature. The lower limit was 39 L/min because of the lower volume, which causes the risk of air entrainment. Figure 15 shows the relationship between the water volume ratio, the cost, and the primary energy consumption. The X-axis means the water level ratio (the daytime hot-water volume/nighttime hot-water volume). The rate that met the above requirements was over 0.4. The volume of hot water storage was under 2 m³ when the ratio was under 0.4. The two-point group showed an inverse trend with respect to the water volume ratio. As the water volume ratio increased, costs increased in proportion to the ratio because of the increased opportunities for operating CO₂HPs, which use relatively cheap electricity. On the other hand, the cost points group varied in areas around 0.85 to 1.0, with some operations having moderate costs and low primary energy. These were the operations with a low water volume at night. In these cases, the supplies of well water were increased to avoid further lowering the water level, and the temperature of the hot water tended to decrease. If the operator avoids the risk of air entrainment, the current pricing system does not provide cost benefits and reduces primary energy consumption. It is recommended that if operators prioritize cost, the water volume ratio should be low, and if operators prioritize primary energy, the water volume ratio should be closer to 1. Another option for matching cost reduction with primary energy reduction is to adjust the price of wood pellets. Various solutions appear in areas where the ratio is close to 1 when the current price is halved. However, such price-slashing does not have a positive impact on the local forest industry. Therefore, the following section examines the regional economic ripple effects.

Figure 14. Well water supply rates in 31 cases.

Figure 15. Relationship between water level ratio, cost ratio, and primary energy ratio.

4. Regional Economic Ripple Effects

The simulation in the previous section showed that the methods for reducing the primary energy and cost were not consistent under the current pricing system. A significant reduction in pellet prices is necessary to achieve these two goals simultaneously, but this could further worsen the financial management of the local forestry industry. Therefore, the financial contribution to the wood pellet price by public sector was considered. The local forestry industry could supply the market with wood pellets at a reasonable price, while companies could purchase wood pellets at a competitive price. The money supported by the public sector circulates throughout the region, reducing the electricity produced by fossil fuels, the funds of which are prone to leak outside the region, to a safe level. The Regional Economic Ripple Effect (RERE) allows us to analyze these situations quantitatively. REREs are the effects of inter-industry transactions that successively affect the output of other industries. The economic ripple effect can be calculated by using the input-output (I/O) table developed by Leontief [22]. The I/O table is a statistical table that shows the trade of goods and services in a certain period in a matrix. There are many previous studies on economic ripple effects that use the I/O table. Santos [23] modeled measures for COVID-19 and estimated financial losses due to the differences between policies. The I/O table has also been used in the analysis of environmental issues. Liu et al. [24] examined the effectiveness of policies on climate change with I/O tables. Huppel et al. [25] used the table to investigate the impact of EU integration on consumer activity.

In general, economic ripple effects derived from I/O tables are classified into three types. The first type is the direct effect, which is the effect of newly generated consumption and investment. The second, that is, the first indirect ripple effects, are the effects induced by the purchase of raw materials and services associated with the direct effects. Last is the second indirect spillover effects, which are the effects induced by increments in private consumption expenditure on the employment income generated by the above two effects.

In this report, the economic ripple effect was defined as the sum of these three effects. The formula for calculating Δx (vector of RERE) is shown in Equation (3):

$$\Delta x = \Delta f + \Delta f \cdot A_1 + \Delta f \cdot A_1^2 + \Delta f \cdot A_1^3 \cdots \infty \quad (3)$$

where vector Δf is the demand for each raw material and service. In this research, Δf means the price of electricity and wood pellets for heating. Matrix A_1 , called the “input coefficient”, is a matrix of the composition ratio of raw materials required to produce one unit of a commodity. When increased demand Δf occurs, the first economic effect is $\Delta f \cdot A_1$. Since the calculation can theoretically go on indefinitely, the following equation represents Δx ; the matrix I in this equation is an identity matrix:

$$\Delta x = \{I - A_1\}^{-1} \cdot \Delta f \quad (4)$$

By introducing matrix M (import coefficients), Equation (3) can be transformed into Equation (4) to separate the intra-regional and extra-regional economic ripple effects. Table 2 shows an example of matrix M . Each value of the table means the ratio of imports in the industrial sector. The value is calculated by dividing the sum of the imports by the sum of demand in the Hokkaido region.

$$\Delta x = \{I - (I - M) \cdot A_0\}^{-1} \cdot \Delta f \quad (5)$$

$$A_1 = (I - M) \cdot A_0 \quad (6)$$

Table 2. Example of matrix M .

	Wood Pellet	Forestry and Logging	Commerce	Transportation	Electricity	...	Others
Wood pellet	0.15	0.00	0.00	0.00	0.00	...	0.00
Forestry and Logging	0.00	0.12	0.00	0.00	0.00	...	0.00
Commerce	0.00	0.00	0.25	0.00	0.00	...	0.00
Transportation	0.00	0.00	0.00	0.35	0.00	...	0.00
Electricity	0.00	0.00	0.00	0.00	0.65	...	0.00
...	...	...	...	...	...	...	0.00
Others	0.00	0.00	0.00	0.00	0.00	0.00	0.55

The local government of Hokkaido publishes a regional economic I/O table every five years. Matrix A_0 and matrix M were calculated with the most recent table, and the electricity and pellet costs obtained from the above simulation were inputted into Equation (5). The RERE of 31 cases with three types of pellets (31 cases $\times$ 3 cases) was used as a parameter.

Figure 16 shows an example calculation result. ‘Not-local’ refers to pellets made outside the region, ‘Normal’ refers to pellets commonly distributed in Hokkaido, and ‘Local’ refers to pellets made inside the region. The figure compares the RERE of the top five industries that benefit from the economic activities of system operation with each pellet. The REREs for electricity were highest in the Not-local and Normal cases. Most of the REREs for electricity were caused by electricity consumption with CO₂HPs. In the Hokkaido area, 88.5% of electricity has been generated with fossil fuels imported from foreign countries. Investments in electricity are not efficient in terms of ripple effects on the local economy. The REREs of wood pellets in the two cases were extended only to transportation and in-store sales within the region. Even in the Normal case, the pellets that contained raw materials from outside the area did not produce REREs. The REREs in the Local case were different from the other cases because the pellets are made from local materials in local factories. Wood Pellets and Forestry and Logging had higher REREs. Moreover, Commerce and Transportation also had a high ripple effect, as demand is induced by the production of wood pellets and materials in the region.

Figure 16. Distribution of regional economic ripple effect.

Figure 17 shows the relationship between the economic ripple effect and other indicators. As mentioned above, the primary energy decreased as the PB's operating time increased. As the water volume ratio was close to 1.0, the cost and economic ripple effect increased because the price of the pellets was higher than that of electricity. RERE varies greatly depending on the type of pellet. In the case of Not-local and Normal, RERE was less than the total cost. In the case of Local pellets, the regional economic ripple effect was twice the total cost. In addition, in the case of Not-local and Normal, RERE did not change much with the water volume ratio, but RERE increased as the water volume ratio increased in the local case. Normal pellets, which are commonly distributed in Hokkaido, also contain many raw materials from outside the region. This causes the results to be the same as those for the Not-local pellets. The Local 100% pellets are pellets purely produced by local forestry. The pellets had a very high economic ripple effect because the supplier used local materials and processed them at plants in the region. The combination of pellet boilers and local pellets effectively creates a good cycle in the local economy and reduces primary energy consumption.

Figure 17. Relationship between water volume ratio and regional economic ripple effects.

The above results suggest that reducing the use of CO₂HPs and operating PBs with local pellets is a reasonable choice for reducing primary energy consumption and regional economic ripple effects. Subsidies for producing cheap wood pellets, which are usually more expensive than electricity, are useful for increasing the use of PBs. However, a decrease in the cost of pellets reduces the RERE. Giving money to users is a better way for the regional economy to circulate the pellets to pellet plants and dealers. However, local pellets often have problems in terms of calorific value and supply systems. It is reasonable to use CO₂HPs as an auxiliary boiler in WWHCs. Therefore, cases with a primary energy of 1000–1500 MJ/day and a water volume ratio of about 0.9 are the optimal solution. In these cases, low daytime and nighttime water volumes likely cause air entrainment when the demand is greater than the assumed demand. More advanced control, such as varying the amount of water controlled during the day and at night depending on a schedule, can optimize safety, primary energy, and REREs at a higher level.

5. Conclusions

This paper investigated the optimization of a combined PB and CO₂HP system installed in a convalescent facility. Both PBs and CO₂HPs are eco-friendly systems that are effective in reducing primary energy consumption. However, such a system has rarely been applied to relatively large facilities. Therefore, methods of operation methods were studied to gain know-how into its operation through trial and error with real operation. As a result, the following was found.

1. The PB could not produce the required output due to a significant shortage in the caloric value of local pellets. This problem can occur in other cases as well.

2. There was a problem in the co-operation of the PB and CO₂HPs, whereby the CO₂HPs were operated only with low efficiency (STCC).
3. The supply of large amounts of well water to the hot-water storage tank often caused the temperature of the hot water supply to be low.
4. PB and CO₂HP used anti-freeze operation in winter, but this caused efficiency to be low and lead to less usage of the CO₂HPs.
5. To solve the above problems, the well water supply rate was reduced, and the water volume of the hot-water storage tank, which was always controlled to be at full capacity, was changed at night and during the day to reduce the primary energy consumption with the WWHC.

However, there are many combinations of well water supply rate, water volume, and hot water supply system operation. In addition, subsidies are essential to promote wood pellets, which are more expensive than electricity. Therefore, their optimization was studied by simulation. As a result, the following was found.

1. The water supply rate was from 39 L/min to 59 L/min to meet the requirements for safe system operation which meets over 50 °C of the hot water supply temperature, and over 2 m³ of the minimum water volume.
2. As the water volume ratio increased, costs increased, and primary energy decreased in proportion to the ratio.
3. The optimized solutions having low cost and low primary energy were in the water volume ratio range of 0.85 to 1.0. The water volumes of those solutions were very low. The operations of CO₂HPs used as auxiliary systems for safety were essential.
4. The REREs were stable in the Not-local and Normal pellet cases. However, in the Local pellet case, the RERE was proportional to the water volume rate. The effect varied greatly depending on the type of pellets. In the case of Local pellets, the RERE was four times greater than that of non-local pellets.
5. As mentioned above, local pellets were inferior in performance to pellets whose performance was guaranteed. However, when considering the reduction of primary energy and the region's economic cycle, the pellets should continue to be used.

Although the study conducted in this paper was limited to the target system, the study methodology can be applied to other systems. Notably, it can provide an important perspective on the balance between the greening and development of a local economy and the stable operation of hot water systems.

When using the system in urban areas, more careful consideration should be given to the emission of polluting gases. When more renewable energy sources are installed in an electric power network, the system will need to be operated with a demand response.

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Nomenclature

PB	The Wood Pellet Boiler
CO ₂ HP	The heat pump system with CO ₂ as refrigerant
WWHC	The well water heating circuit
STCC	The storage tank circulation circuit
RERE	The economic ripple effect
I/O table	The economic Input Output table
V_T	The volume of the storage tank, m ³
q_{WS}	The supply flow rate of the well water, m ³ /s
q_{HP}	The supply flow rate of the CO ₂ HP, m ³ /s
q_{hs}	The hot water supply to the demand, m ³ /s
$c\rho$	The volumetric heat capacity of water, J/m ³ /K
θ_T	The temperature in the hot water storage, °C
θ_{WS}	The temperature of the well water supply, °C
θ_{HP}	The temperature of the hot water supply through CO ₂ HP, °C
θ_{PB}	The temperature of the hot water supply through PB, °C
θ_O	The temperature around the hot water storage tank, °C
U	The thermal transmittivity of storage tank wall, W/m ² /K
S	The surface of the storage tank; the floor area of the tank is 9 m ²
Δx	The regional economic ripple effect
Δf	The demand for each raw materials and services
A_n	The input coefficient
M	The import coefficient

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