

A Study on Sustainable Energy Systems for Small Villages in Fukushima

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Abstract

We investigated the design and operation of distributed energy systems for the central area of Mishima Town in the Oku-Aizu area of Fukushima Prefecture. These systems were tailored to the characteristics of the region. Although we found that the deployment of an energy system utilizing forest biomass resources was desirable from the perspectives of CO₂ emissions and economic circulation based on local natural resources, the cost of energy was relatively high. Based on these results and related information, we considered the processes required for implementing energy systems utilizing forest biomass resources. Our results show that to create sustainable communities based on renewable energy in rural areas with low population density, it is important to integrate energy system development with community development from a medium- to long-term perspective.

Key words : autonomous distributed system, mathematical optimization, mixed integer linear programming, regional revitalization, renewable energy

1. Introduction

Interest in renewable energies has grown against the backdrop of global environmental issues, with the Great East Japan Earthquake revealing the vulnerabilities of large-scale centralized electric power supply systems. These two considerations have led to increased nationwide momentum to promote the introduction of distributed energy systems utilizing renewable energies (Nakata, 2015). In addition, frequent abnormal weather events such as heavy rains and snowfalls in recent years further have spurred this trend. This is particularly of great concern in Fukushima Prefecture, Japan, which is now suffering from all of these problems, necessitating a comprehensive solution for revitalization.

Up to now, however, technology and policies related to resources and energy have been regarded as national and global issues and, therefore, “given conditions” that could not be altered at the level of local living and economies. Adverse impacts have arisen due to the large gap between the given conditions and local situations. For example, in mountainous and other remote areas, energy supply infrastructure such as gas pipelines has not been sufficiently developed. Thus energy prices have tended to be higher there than in urban areas. Rural

communities have been unable to implement effective measures to address such situations. Especially in cold regions where there is great demand for space heating and hot water supply, utility costs are a burden for households. Furthermore, inadequate space heating and hot water supply systems along with poor building insulation lower residents’ quality of life.

Meanwhile, Japan’s 5th Basic Environmental Plan has advocated maximizing the vitality of regions by using regional resources to build self-reliant, decentralized societies based on the characteristics of regions and, to this end, proposes the concept of regional circular and ecological spheres that complement and support regional resources. The introduction of renewable energy is regarded as a substantive measure that will contribute to the creation of such regional circular and ecological spheres (Shirai, 2018a; Shigeto et al., 2018). Effective use of forest resources has been recognized as a key issue for revitalizing local economies and sustainable regional development in rural communities especially in mountainous areas (Uragami & Itogami, 2007). In addition, development of technologies such as small biomass cogeneration systems for converting forest resources into energy are being actively promoted (Japan Woody Bioenergy Association, 2017a, b).

Previous studies related to sustainable community development in mountainous areas have been carried out at the village or regional scale comprising single or multiple local governments. Research at the village scale has focused on specific energy projects and their impacts (Asano & Takaguchi, 2015). A number of studies at the regional scale have focused on regional circulation effects of biomass and other resources (Sumitomo *et al.*, 2015; Miura *et al.*, 2018; Nakamura & Shibata, 2013). However, since these previous studies have been carried out in parallel at each scale, inter-scale effects—for example, the impact of village-scale energy systems on resource circulation at a regional scale—have not been adequately investigated.

Therefore, this study examined the feasibility of transition to next-generation energy systems utilizing local resources in mountainous villages of Japan, and quantified the impacts of introducing such systems on the balance of resource supply and demand, as well as on the regional environment and socio-economy.

2. Study Area and Data

2.1 Study Area

This study targeted the central area of Mishima Town in the Oku-Aizu area of Fukushima Prefecture. According to the 2015 census, the population of Mishima was 1,792, and the proportion of the population 65 or older had already reached 49% (compared to the average for Japan of 26.6%). The main industries included construction and electric power connected with a local Tohoku Electric Power hydroelectric power plant (maximum output 94,000 kW), followed by agriculture, forestry and tourism. The area of the town is 1,518 km² with approximately 80% of that area being forested. Therefore, regional development based on effective utilization of woody biomass resources as energy has become a goal of public policy. The use of woody biomass resources, however, has been limited to the introduction of wood pellet stoves and firewood stoves in

some public facilities and houses.

Figure 1 and Table 1 provide an outline of the study area. The area inside the dotted line in Fig. 1 is the central area of Mishima Town, which is the subject of this study. Facilities such as the town hall, prefectural hospital, Aizu Miyashita Station and welfare facilities are located centrally and play a central role in the town. Solar panels have been installed on the welfare facilities. Although housing accounts for only a small proportion of buildings in the central area of the town, that area has the town's largest population concentration.

We estimated spatial information for the area that was required for energy system assessment. This included the length of the heat distribution pipes that would be required for deploying district heating and the area of land where solar panels could be installed. The pipe length was assumed to be the length of the shortest road network required to connect the buildings in the area. It was assumed that solar panels would be installed on the roofs of buildings in the central area of the town. However, since roof area data were not available, the built-up area was assumed to be the roof area. Building data were estimated based on information from Zenrin Tatemono Pointo (2014 version) and road network data based on Zenrin Data Zmap-Town II (2015 version) using GIS.

2.2 Establishing the Renewable Energy Supply Potential

Since the renewable energy supply potential depends on the characteristics of the region, we set assumptions regarding the biomass resources and photovoltaic power generation potential required for subsequent analysis. The NEDO estimate (2011) for available biomass resources (forest residuals from harvesting and trimming) is 4,085 tons/year for Mishima Town and 43,746 tons/year if the resources of the four nearby towns and villages (Tadami Town, Yanaizu Town, Kaneyama Town, and Showa Village) in the Oku-Aizu area are included. This value is referenced in the evaluation of the regional circular sphere. The photovoltaic power generation potential was set based on monitoring data collected by the authors in Mishima Town. Figure 2 shows the power generated by a 1 kW solar panel. The figure shows hourly data for one week from January 1 to 7 as well as monthly data. The Oku-Aizu region is a heavy-snowfall area that receives approximately 60 cm of snow annually in the winter. The

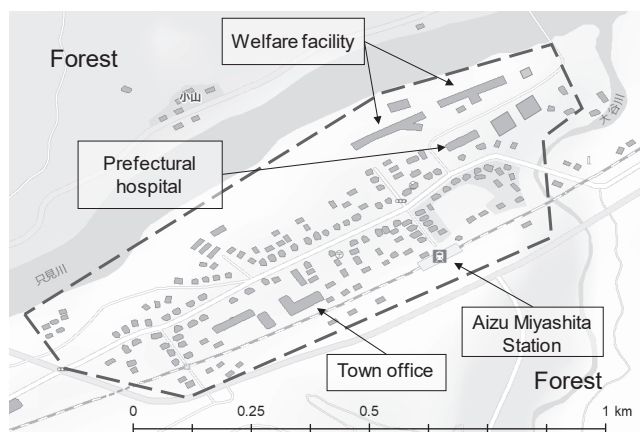


Fig. 1 Study area (central district in Mishima Town).

Table 1 Overview of study area.

No. of Households	Households	211
Population	Individuals	390
Building Floor Area	[m ²]	64,339
Conduit Length	[m]	4,663
Roof Area	[m ²]	32,262

effect of this snowfall is confirmed as reduction of power generation during the winter months in Fig. 2. It is assumed that the solar panels were covered with snow from Jan 3 to 6. These data are referenced in subsequent analyses as the potential amount of photovoltaic power generation.

2.3 Energy Demand

Hourly energy demand data were set for the study area for the following use categories: electric power, cooling, heating and hot water supply. First, annual energy demand was calculated by multiplying the floor area for each use in each neighborhood by the energy load intensity. Then, hourly energy demand was

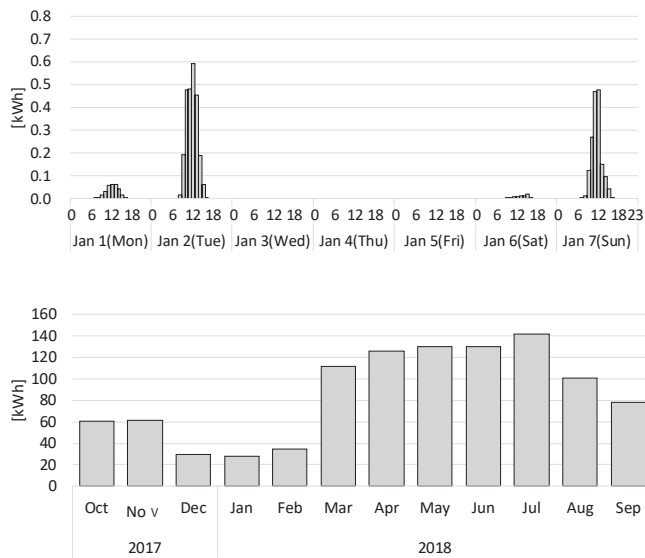


Fig. 2 Monitoring data of photovoltaic power generation in the study area.

The upper graph for each case shows the hourly data (for one week in January). The lower figure shows the monthly data.

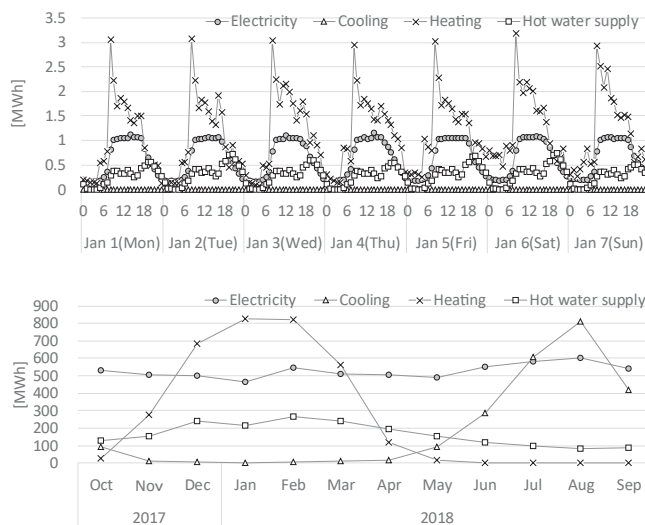


Fig. 3 Energy demand in study area.

The upper graph for each case shows the hourly data (for one week in January). The lower figure shows the monthly data.

calculated by multiplying the annual energy demand by the monthly and hourly proportions. The values reported by Kashiwagi (2008) were used for the ratio of energy load intensity and for monthly and hourly proportions; to reflect circumstances in the Tohoku region for energy load intensity, we used the correction coefficient from Japan District Heating & Cooling Association (2002). Regarding the housing sector, the authors monitored energy consumption at 12 all-electric homes in Mishima for one year from October 2017 to September 2018. Hourly and monthly electric power consumption was measured by meters for each use category, and power consumption for each use category was corrected using the measurement results. Figure 3 shows the calculated energy demand results (hourly values for the week of January 1 to 7 and monthly values for the year) for the study area.

3. Model

3.1 Overview of the Planning Process Model

To examine the effect of introducing alternative energy systems, it is necessary to evaluate detailed system designs and optimal operation of each general system type comparatively. In this study, the planning process model reported in previous studies (Togawa et al. 2017; Togawa et al., 2020a) was used to determine the conditions resulting in minimal cost for design and operation. The basic structure of the planning process model is shown in Fig. 4.

An energy system converts power supplied by the grid or fuel from outside the system (gas, kerosene, biomass resources, etc.) into electric power, heating and cooling, and hot water supply for use on the demand side. First, we set up an energy system study framework. Figure 4 shows a general structure including all candidate energy systems that is referred to here as the

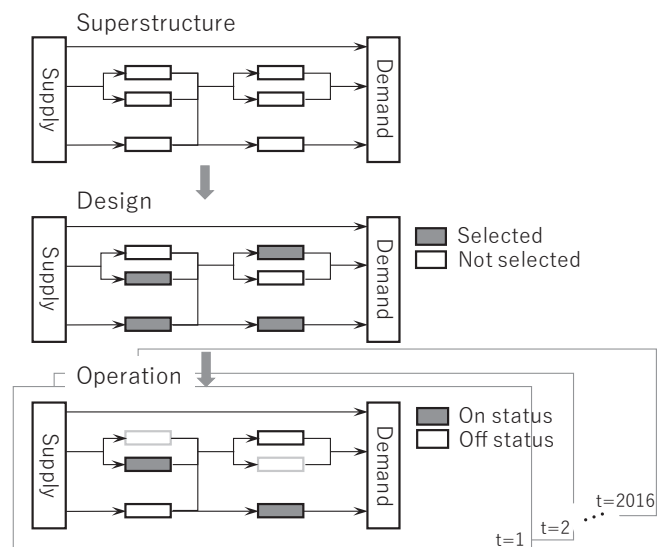


Fig. 4 Basic structure of planning process model.

“superstructure,” following the nomenclature used in previous research (Yokoyama, 2014). The superstructure is represented by the subsystems that represent the candidate devices that make up the system and the potential flows of energy between them (input/output relationships).

Next, we simultaneously specified the system configurations that minimize the cost function, which combines flow values such as fuel consumption with stock values, such as installed capacity, and the operating plans for each season and time period. Fuel consumption was calculated by multiplying the energy demand of the buildings shown in Fig. 3 by the energy conversion efficiency of the equipment. Depending on the purpose, a subsystem can be selected from the superstructure, and the equipment to be operated and the input/output level for operation can be specified for each season and time for the selected equipment. For this reason, equipment that needs to be operated even once must be selected at the design stage and the capacity of the equipment must be greater than or equal to the annual maximum output value.

However, for this study, because the calculation load would be prohibitively high if the analysis were performed for 8,760 hours a year, the calculations were performed for 2,016 hours based on the data for one week extracted from each month. It was also assumed that the same type of energy system was installed in all the buildings in the study neighborhood.

3.2 Establishing the Superstructures

Taking into consideration the availability of resources and technological progress (Nakamura *et al.*, 2018) in mountainous areas, we assessed the impact of three different cases involving introduction of alternative energy systems that combine biomass-related technologies and photovoltaic power generation with the currently deployed system. Figure 5 shows the superstructure of the system. Here, the energy systems were treated as an aggregated unit for a given neighborhood; the capacity of each component of the energy systems could be set from continuous variables except in the case of biomass cogeneration (BCHP: Biomass Combined Heat and Power), which has a relatively large capacity per unit.

Case 1: Conventional System

Room air conditioners, kerosene heaters and gas water heaters are used for cooling, heating, and hot water supply, respectively. The energy supply sources are grid power, kerosene, and LPG (liquefied propane gas). According to survey results, this is the most common system configuration in the study area (Nakamura *et al.*, 2018).

Case 2: Photovoltaic Power Generation + All-Electric System

All energy is supplied by the grid and solar panels. Room air conditioners and heat pump water heaters are used for cooling, heating, and hot water supply. The installation of storage batteries and heat storage tanks is possible. As mentioned above, the maximum installation

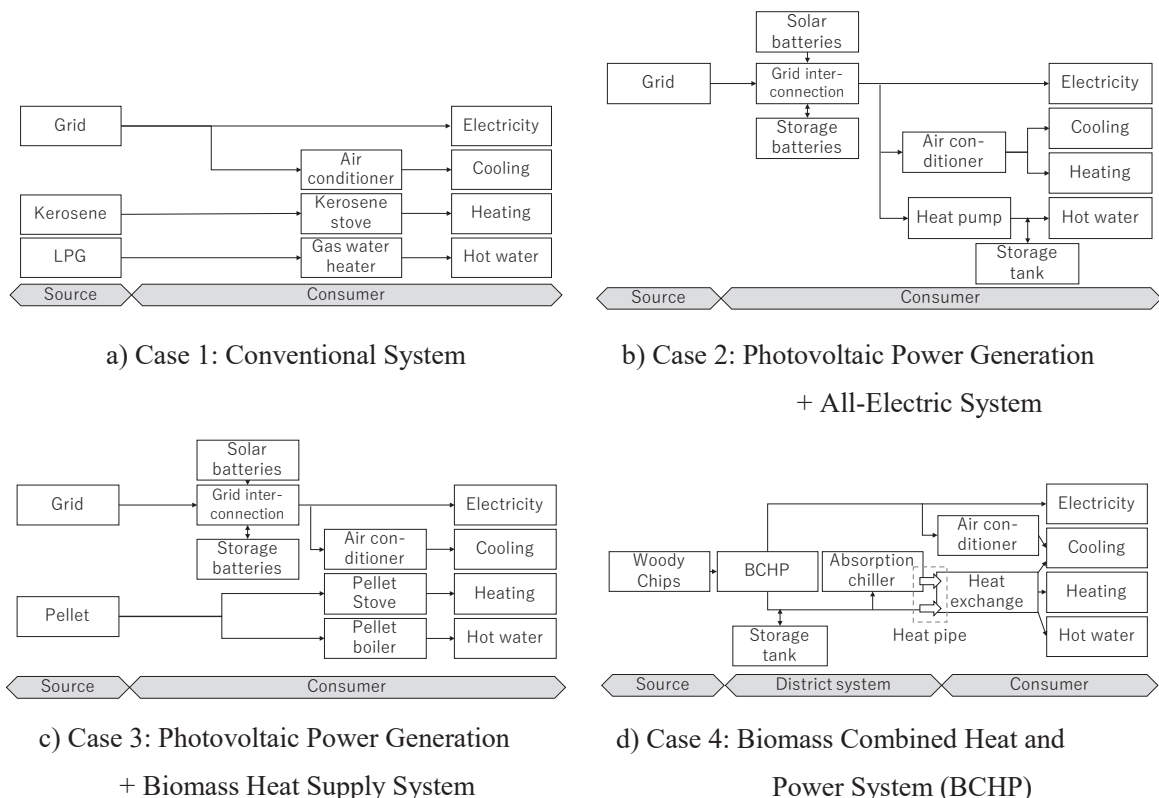


Fig. 5 Energy system alternatives.

Table 2 BCHP unit parameter values.

Generation System Type	Electric Power Output	Generation Efficiency	Thermal Efficiency	Cost (1,000 JPY/Year)		
				Capital Costs	Maintenance	Labor
Gasifier	45 kW	0.25	0.56	2,000	460	2,700
Gasifier	180 kW	0.30	0.45	22,000	5,900	2,700
ORC	600 kW	0.19	0.69	74,000	9,100	5,400

Sources: Japan Woody Biomass Association (2017a, b), Nakagawa (2015), Bartenstein (2015).

area for solar panels equals the building roof area. In recent years, all-electric houses, which are considered to be one of the directions for future energy system conversion, have been constructed in the study area (Mishima Town, 2018).

Case 3: Photovoltaic Power Generation + Biomass Heat Supply System

Although grid power and solar photovoltaic panels are used as in Case 2, stoves and boilers that use biomass pellets as fuel are used for heating and hot water supply. Given that the stoves and boilers are installed by each customer, installation of heat distribution pipes is not necessary. This scenario assumes the deployment to each customer of photovoltaic power generation and biomass heat supply systems that have already been installed in some buildings in the study area.

Case 4: Biomass Combined Heat and Power System (BCHP)

The BCHP system generates the necessary electric power and uses the waste heat for heating, cooling and hot water supply. Therefore, a heating pipe network is required for the district. BCHP assumes the deployment of a 10 to several hundred kW-class system similar to those being developed mainly in Europe. The available BCHP devices are shown in Table 2, with up to two units being selectable for each system. This scenario proposes the introduction of leading-edge technology of which only a few examples exist in Japan.

The set values of other components required for each energy system were specified based on vendor catalogs, and the unit prices for electricity, kerosene and LPG were set based on the prices in the study area (Togawa et al., 2017).

4. Results

4.1 System Design and Operating Plans

Table 3 gives a summary of the system designs for each case and lists the installed capacity of major components of the energy systems shown in Fig. 5. First, we confirmed the capacity of the solar photovoltaic systems for Cases 2 and 3. In Case 2, a photovoltaic system with a capacity equivalent to about 60% of the installable area (building roof area) was selected. The capacity of the photovoltaic system in Case 3 was slightly smaller than in Case 2 due to the lower electricity demand

Table 3 Summary of system components.

Case 1	Room Air Conditioner	(kW)	3,630
	Kerosene Stove	(kW)	3,853
	Gas Water Heater	(kW)	524
Case 2	Photovoltaic Panels	(kW)	1,922
	Room Air Conditioner	(kW)	3,630
	Heat Pump Water Heater	(kW)	598
Case 3	Photovoltaic Panels	(kW)	1,817
	Pellet Heater	(kW)	3,853
	Pellet Boiler	(kW)	475
Case 4	BCHP	(kW)	870
	Storage Batteries	(kWh)	5,359
	Heat Exchange Unit	(kW)	6,380

for heating and hot water, which were covered by wood pellets instead. Next, we examined factors for determining the capacity of the pellet stoves and the pellet boilers in Case 3 by comparison with the demand shown in Fig. 3. The installed capacity of the pellet stoves was set at 3,853 kW, which corresponds to the peak heating demand in winter (January). For the week shown in Fig. 3, the peak heating demand was about 3,000 kW. However, as the peak times for residential and business systems differ, the combined total of the peak heating demands is about 3,853 kW. On the other hand, the installed capacity of the pellet boiler was set at 475 kW, which is about half the peak demand for hot water supply in winter (January) (about 800 kW for the week shown in Fig. 3). Given the high cost of biomass boilers, it was assumed that heat storage tanks would be installed to optimize the systems and minimize boiler size.

4.2 Operating Plans

Next, to confirm how the systems operated, we examined the energy supply and demand by hour and month (Fig. 6). The supply and demand data for electricity and hot water for each case are presented. The upper graph for each case shows the hourly data (for one week in January) while the lower figure shows the monthly data. The equipment used to supply energy in response to demand is shown. Negative values for the supply from storage batteries and hot water tanks in the hourly diagrams indicate energy is being stored. First,

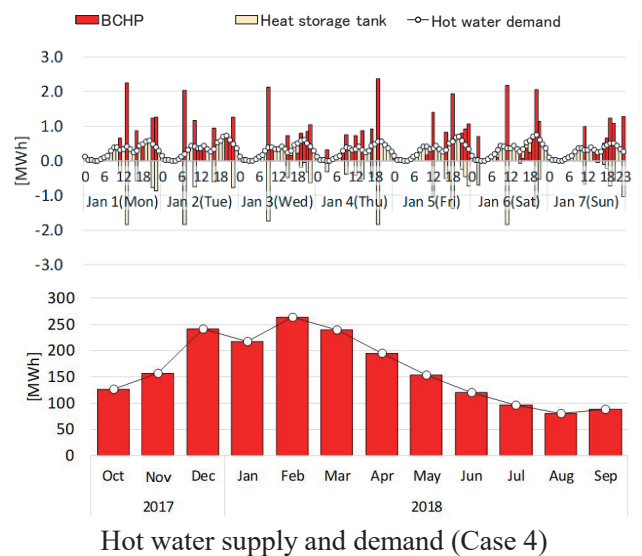
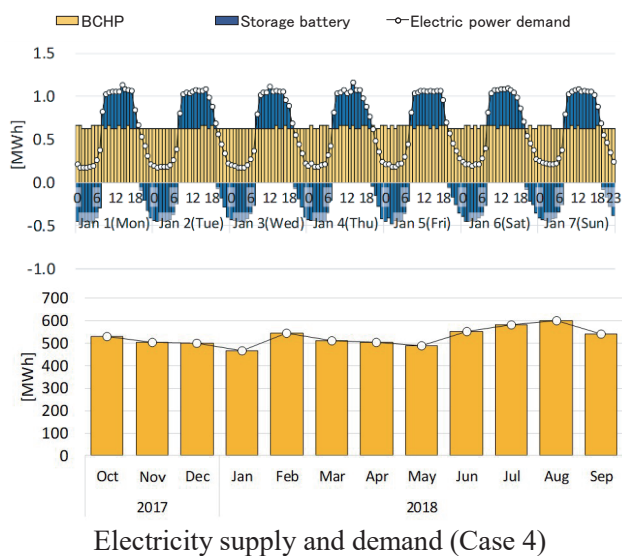
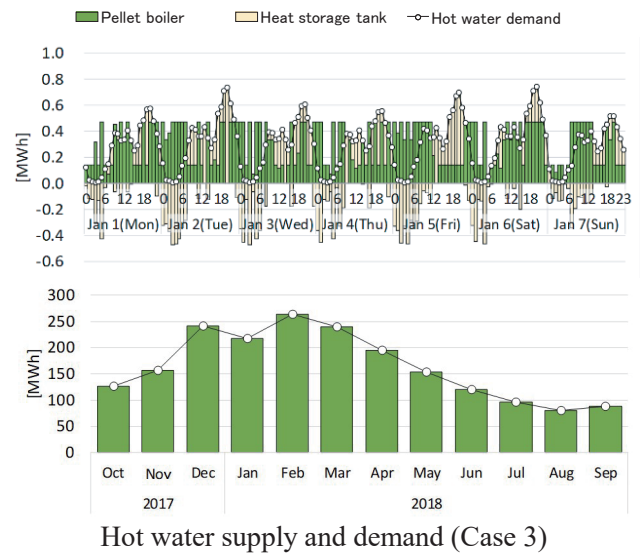
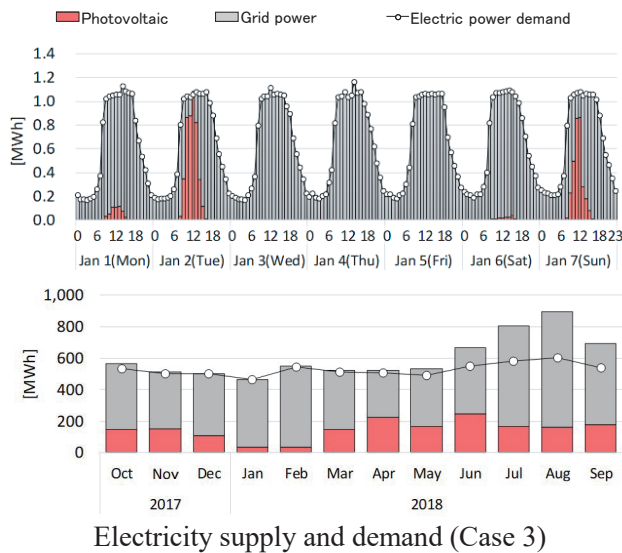
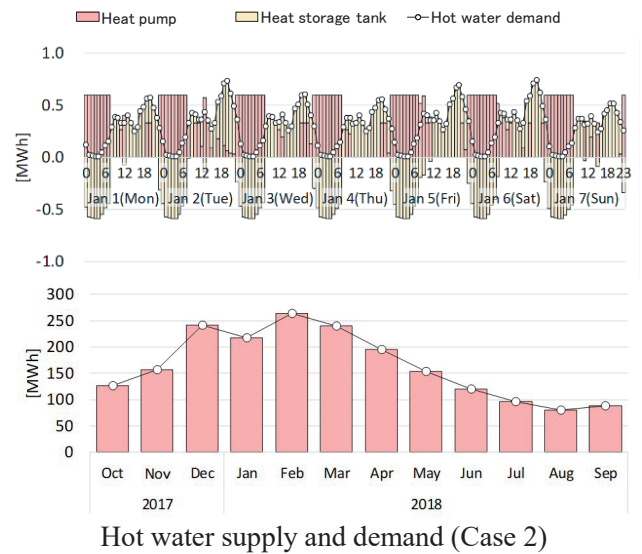
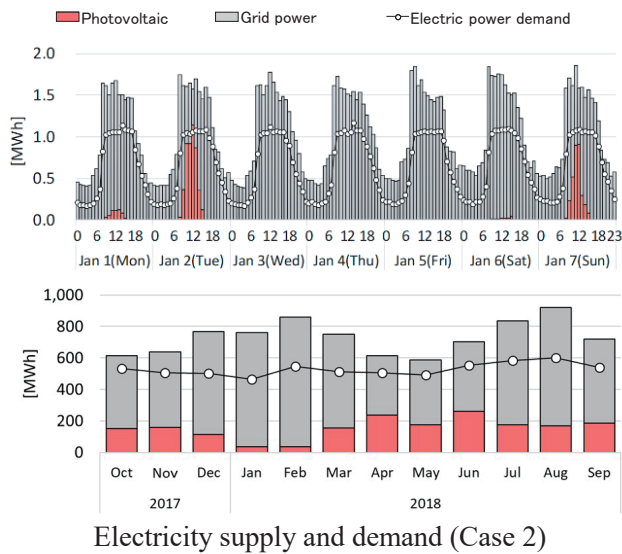


Fig. 6 Supply and demand data for electricity and hot water in each case.

The upper graph for each case shows the hourly data (for one week in January). The lower figure shows the monthly data. Negative values for the supply from storage batteries and hot water tanks in the hourly diagrams indicate energy is being stored.

from the electric power supply and demand for Cases 2 and 3, it can be seen that photovoltaic power generation exhibits substantial seasonal and daily fluctuations, with the amount of power generation in winter being particularly limited. Furthermore, from the hourly supply and demand for hot water supply in Case 2, it can be seen that the heat pump water heater is operated using low-cost nighttime electricity. In addition, from the hourly supply and demand for hot water supply in Case 3, it is evident that hot water is stored during the low-demand period with the 475 kW biomass boiler operating at full capacity, which is lower than the peak demand; the stored hot water is consumed during the peak demand period in the evening. Similarly, from the results for Case 4, it can be seen that the BCHP system operates steadily at 870 kW throughout the year, storing surplus electricity at night when demand is low and distributing the stored electricity during peak daytime demand periods when the BCHP system output is lower than demand. As above, appropriate system designs and operating plans were derived for each case.

4.3 Impacts of System Deployment

Figure 7 shows the results of estimating energy costs for the entire study area for each case. The energy cost including equipment associated with Case 1 was approximately 300 million JPY. The energy cost reductions associated with Cases 2 and 3 were on the order of 20%. However, Case 4 resulted in a 34% increase in cost.

Next, we examined the effect of system deployment on economic circulation. In Cases 1 and 2, most of the economic benefits are thought to flow out of the region. The items that are likely to contribute to regional economic circulation (personnel costs, maintenance costs, pellet charges, chip charges) amounted to 52 million JPY for Case 3 and 175 million JPY for Case 4. These costs only accounted for approximately 1% in Case 3 and 3% in Case 4 of Mishima Town's total production, which is 6.1 billion JPY (Ministry of the Environment & Value Management Institute, 2013). These results indicate the

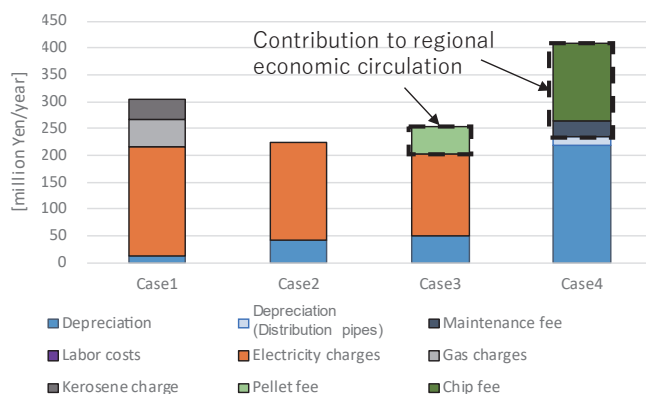


Fig. 7 Cost evaluation results.

importance of expanding measures beyond the central area to the surrounding areas if they are to have an impact on revitalizing the regional economy.

Figure 8 shows the impact of each case on CO₂ emissions and emissions reduction. Cases 2 and 3 reduced CO₂ emissions by 28% and 43%, respectively, compared to Case 1. In Case 4, CO₂ emissions were zero because energy from fossil fuels was not used. Using a CO₂ transaction price of 4,355 to 8,710 JPY/ton-CO₂ (40 to 80 USD/ton-CO₂) from the World Bank (2019), the economic value of these CO₂ reductions is estimated to be 6 to 47 million JPY. In all cases, the value is about 10% to 40% compared to the increase/decrease in direct energy costs, indicating the importance of taking the value of environmental benefits into account when selecting energy systems.

Next, we examined the consumption of biomass resources. Here, the amount of woody biomass resources used as raw materials was evaluated in a unified manner. We assumed that both pellets and chips were produced from woody biomass resources with a moisture content of 50%, which is equivalent to that of raw wood, and converted biomass mass into energy units assuming 1 kg = 2.33 kWh. The results are shown in Fig. 9 together with the available woody biomass resources in Mishima Town. In Case 3, the consumption of biomass resources was approximately 40% of the amount available to Mishima

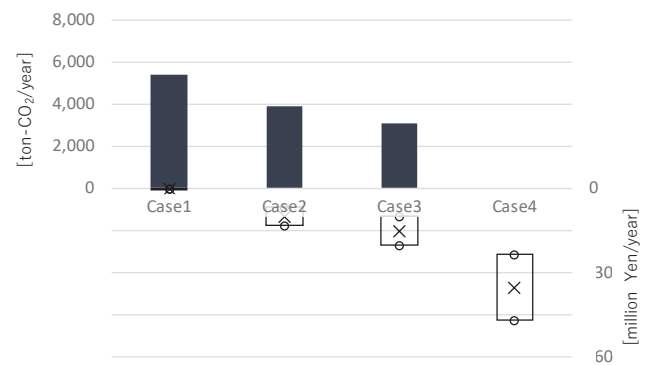


Fig. 8 Results of evaluating CO₂ emissions and the economic value of these CO₂ reductions.

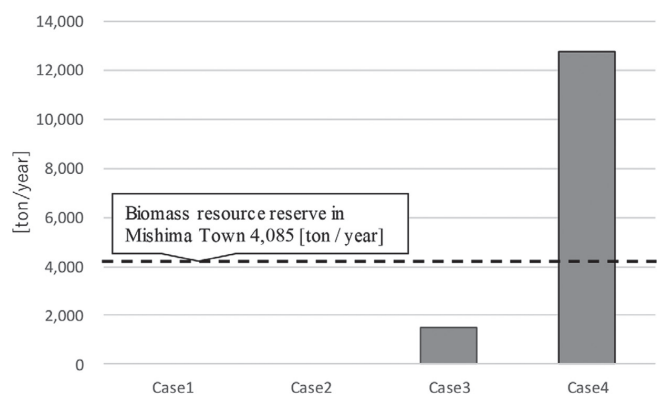


Fig. 9 Results of evaluating biomass resource consumption.

Town, while the consumption in Case 4 greatly exceeded available resources. However, in all cases, the amount consumed was small compared to the total annual biomass resources available in the Oku-Aizu area (48,736 tons/year according to NEDO, 2011). Thus, we believe that the use of biomass energy can contribute to revitalization of forestry in Mishima Town and the Oku-Aizu area.

5. Discussion

As shown in Fig.7, we found that it would be difficult to introduce neighborhood energy systems based on BCHP due to the substantial initial investment associated with neighborhood BCHP systems. However, the system is expected to have a positive regional effect (Figs. 8 and 9). Also, these results are based on the current socio-economic situation. It is important to take into consideration that technological development of small-scale energy supply systems suitable for neighborhood energy systems is actively progressing (Murugan & Horák, 2016). In particular, small 10 kW-class biomass cogeneration system units have been developed and are being deployed mainly in Europe. In Japan, studies have been carried out addressing component technologies related to biomass power generation. Yanagida *et al.* (2015) analyzed the relationship between the break-even point and raw material procurement cost for biomass power generation businesses at various output scales. They found that, even if a relatively high feed-in-tariff purchase price is assumed, the amount of power generated must be 5 MW or greater to be profitable. Sasauchi (2015) examined the technical characteristics of steam turbine power generation, gasification with gas engine power generation, and ORC (Organic Rankine Cycle) power generation, which are typical power generation methods for woody biomass, and reviewed the profitability of small-scale projects for each method. They found that the steam turbine method is not profitable for small-scale power generation businesses of about 2 MW. However, profitability is greatly improved for gasification with gas engine power generation and ORC power generation, which can supply heat along with power, indicating the business potential of such systems. Similarly, Kuboyama *et al.* (2016) and Komata *et al.* (2016) point out the need for cogeneration when using small-scale biomass generators. As described above, technologies for practical distributed energy systems that can contribute to local economies by utilizing forest resources in mountainous areas are being developed. The output of the 870 kW BCHP examined in this study was less than half that of the 2 MW-class systems evaluated in the above studies. Moreover, as can be seen from Fig. 6, the efficiency of heat utilization is not always high. These points along with those mentioned above indicate that increasing

demand and improving heat utilization efficiency are challenges that must be overcome.

Based on the above, the key to implementing local energy systems is improving energy utilization efficiency through cogeneration. However, as the ability to transport thermal energy is limited, efforts must be integrated with regional development plans that include, for example, concentrating energy consumers. In a previous study (Shirai, 2018b) field studies were conducted in eight pioneering examples of integrated energy business and community development, clarifying the roles played by stakeholders such as local companies, citizen networks, regional organizations and universities. It has also been pointed out that these examples are not based on top-down deployment but, rather, the result of co-creative processes by diverse stakeholders in a community. A case study conducted by the authors in Shiwa Town, Iwate Prefecture, which is an environmentally leading municipality, found that budding efforts in resource circulation that started around 2000 have spawned other activities including the development of various spaces by diverse stakeholders through co-creative processes (Togawa *et al.*, 2020b). These results show that to create sustainable communities based on renewable energy in rural areas with low population density, it is important to integrate energy system development with community development from a medium- to long-term perspective. However, no general design schemes that can be applied to different complex problems have been sufficiently developed, and past approaches have tended to rely on local experience. In our research as well, we examined a top-down method for designing a distributed energy system. Frameworks for bottom-up design of sustainable communities that complement this top-down approach need to be developed.

In addition, various social benefits associated with deployment of distributed systems have also been identified. These include the stabilization of employment by building energy supply systems in local communities, enhanced continuity of the energy supply in the event of a disaster, and improved safety and security of the region (Nakata 2015). Therefore, it is important to develop systems that are competitive in function with large scale systems while also being tailored to the unique circumstances of each community through co-creative processes and multidimensional perspectives that cover the environment, economy and society.

6. Conclusions

In this study, we developed designs and operating plans for and evaluated the deployment potential of alternative energy systems taking into account the structure of the neighborhoods that made up the area and the supply characteristics of renewable energy. Our findings were as follows:

- Based on hourly energy supply and demand, we developed a planning process model that can simultaneously derive optimal energy system design and operating plans and conducted analyses using data obtained through monitoring in the actual community.

- We conducted analyses using models based on information that we had obtained for the central area of Mishima Town, Fukushima Prefecture, which has characteristics typical of the mountainous areas of Japan. Our results showed that it is possible to reduce energy costs by introducing a fully electrified system that uses photovoltaic power generation. We also showed that the introduction of biomass boilers and biomass cogeneration systems that utilize forest biomass resources is desirable from the perspective of CO₂ emissions reduction and local resource circulation.

- We considered issues for implementation of regional energy systems in rural areas with low population densities. We found that a framework was necessary for comprehensively designing sustainable local communities that incorporates regional development in the surrounding area with selection of appropriate distributed energy systems that are tailored to regional characteristics.

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