Industrial Symbiosis Centered on a Regional Cogeneration Power Plant Utilizing Available Local Resources
A Case Study of Tanegashima

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Summary

Plant-derived renewable resources have the potential to enable the simultaneous generation of high-value-added products, such as foods, with energy, such as electricity and thermal power. Much of the heat cogenerated from renewables in power plants has been discarded because of the geographical and temporal gaps in heat supply and demand. In this study, we aim to devise an effective industrial symbiosis (IS) for a regional combined heating and power (CHP) plant utilizing local renewable resources. For the actual region of IS, the island of Tanegashima in Japan was adopted, where sugarcane is planted as a base industry. Through a thermodynamic analysis of the energy flows in a sugar mill, it was demonstrated that large amounts of heat were discarded from the sugar mill, even though the quality of heat was high enough for power generation or other energy demand. This is partly because some of the renewables have been regarded as wastes in the production of foods or other high-value-added products. At the same time, scenarios were defined and analyzed on the integrated use of locally available lignocellulosic biomass to increase the operation ratio of an existing bagasse-based CHP system. Through both periods with and without sugar production, additional heat and power can be made available by decreasing the energy loss and through IS.

Introduction

The use of plant-derived materials and energy has been regarded as one method to mitigate environmental impacts, such as greenhouse gas (GHG) emissions and fossil resource consumption (e.g., Nguyen et al. 2011; Kikuchi et al. 2013), with the possible increase of other environmental impacts, as discussed in previous literature (e.g., Weiss et al. 2012). The utilization of by-products of plant-derived production, which we call biomass, can allow highly efficient use of these resources. For example, all sugar mills and some sawmills have implemented cogeneration or combined heat and power (CHP) plants utilizing biomass. The residue from the production of raw sugar, bagasse, and wood residues, such as sawdust, are used as fuels in these CHP plants. This can be regarded as a measure for demand-side energy saving, which facilitates shifting fuel sources from fossil to biomass.

Life cycle assessment (LCA) has been used to evaluate the environmental performance of bioenergy systems that use biomass residues, including those that specifically use bagasse and sawmill residues (e.g., Guerra et al. 2014; Hitoe and Hat-tori 2011), biogas from anaerobically digested organic residues (e.g., Fukui 2009; Pöschl et al. 2010), and the production of liquid biofuels from waste (e.g., Nguyen and Gheewala 2008).
LCA studies on CHP systems have been conducted, and increasingly so in developing countries, mainly in Southeast Asia (Cherubini and Strømman 2011). These studies have shown that GHG emissions can be reduced by utilizing biomass as fuel; for example, see the review by Muench and Guenther (2013). LCA has also been used to assess the potential benefits of biorefineries, where, with crude oil refineries, multiple products are generated from a feedstock (e.g., Cherubini and Jungmeier 2010). Studies evaluating biorefineries have concluded that the replacement of fossil resources with renewable biomass resources can be achieved with sufficient low environmental impact. The added value of energy is not always higher than that of the high-value-added products we have historically produced from plant-derived resources. Considering renewable resources, especially plants and crops, the balance of their final products has also become a critical issue in implementing new factories to utilize them and should be carefully addressed by considering new technology developments to avoid competition between food and energy production (Ohara et al. 2005, 2012).

Industrial symbiosis (IS) should be an effective measure to balance the supply and demand of energy in a regional community. After the “uncovering” of IS (Chertow 2007), the standard of promoting eco-parks (Geng et al. 2008) and the systematic categorization of symbiosis types (Chertow and Ehrenfeld 2012) have been proposed. Many case studies on IS have been analyzed in the context of LCA (e.g., Sokka et al. 2010; Van Beers et al. 2007; Chen et al. 2012). By sharing the excess energy or materials among incorporated industries, resource use and waste can be reduced while improving the environmental performance (Jacobsen 2006). Energy sharing can also improve the efficiency of the utilization of fuel for power and heating. Therefore, IS has the potential to increase the effectiveness of CHP plants. Power generation efficiency based on thermal-energy conversion plants has a scale dependency: For internal combustion-type generation systems, a larger scale is generally more efficient regarding resource use and economic aspects (Kikuchi et al. 2015). For smaller plants, which have lower power-generating efficiency and a higher proportion of outputted heat, exhaust heat recovery can be more important than the production of electricity because of the temporal and spatial gaps in supply and demand (METI 2014). Although this can decrease the incentive for installing small- or medium-sized CHP technologies, distributed energy systems have the potential for upgrading the resiliency of energy systems (McLellan et al. 2012) toward devastating disasters, such as the Great East Japan Earthquake (Fukushima et al. 2011), and developing district heating systems by sharing excess heat to reduce emissions (Gebremedhin 2012), or increasing the efficiency of utilizing resources considering exergy loss (e.g., Çomakli et al. 2004).

Tanegashima is one of many remote islands in Japan that have independent electricity grids, and it is highly reliant on imported fossil fuels for power generation. Tanegashima has a large sugar production industry that uses bagasse for heat and power production, but only during the production season, leading to unused energy generation capacity during the off season. Making use of this unused capacity could reduce Tanegashima’s dependency on imported fossil fuels (FFs). Although FFs used on remote islands have relatively higher costs and environmental impact, only the sugar industry has invested in biomass-derived energy in Tanegashima.

In this study, IS and improved utilization of existing heat and power systems were explored for Tanegashima, using the bagasse CHP system as the primary power generation unit, with the aim of making better use of existing energy production units and increasing their use of local renewable fuels. Based on a detailed energy analysis of the sugar mill, unused excess energy originating from bagasse is specified and the qualities of energy are carefully analyzed. Through the detailed energy analysis of the unused and potentially usable biomass-derived energy from the sugar mill, scenarios for future energy systems in Tanegashima are designed and analyzed by modeling applicable technologies. In the scenario analysis, the utilization of equipment in current operation, that is, the bagasse-derived CHP plant at the sugar mill, is considered as a main premise. The current seasonal operation has changed to a year-round operation by using biomass resources for not only excess bagasse, but also local biomass resources as sources of energy.

**Materials and Methods**

**Industrial Symbiosis and Energy Analysis of Sugar Mill in Tanegashima**

The concept of a possible IS on the existing in-house CHP system of plant-derived production processes is shown schematically in 1. This concept enables the utilization of the residues from the production of product B as a fuel in an energy plant with the biomass-derived fuel originally utilized in the production of product A. This results in the acquisition of biomass-derived heat and power for the production of product B as shown in figure 1. In Tanegashima, bagasse can be regarded as one of the most important and feasible biomass available in stable quantities. A bagasse boiler and power generation system is now under operation and available as the basis of regional energy generation shown in figure 1. An energy flow analysis of the sugar mill is required for scrutinizing the possible roles of existing plants in IS in Tanegashima. Woody biomass is also available as a fuel for the regional energy plant in figure 1. Bagasse and such other lignocellulosic biomass can collaborate in various ways with the existing bagasse boiler or other heating devices, such as distributed stoves. These options were tested in a scenario analysis.

Figure 2 shows the process flows in the sugar mill in Japan and the energy flow within the sugar mill in Tanegashima. Actual operation records extracted from the distributed control systems (DCS) in the mill were interpreted together with the results of interviews with the on-site experts in sugar production. The unused energy from the sugar mill, including both waste heat and the potential excess bagasse under the assumption of the modification of, for example, steam pipes for reducing heat loss, was also analyzed (see also the supporting information available on the Journal’s website).
**Scenario Analysis on Industrial Symbiosis Centering on Existing Energy Plant**

**Introduction to Scenario Analysis**

This scenario analysis aims to reveal which combinations of the technologies and the resources are feasible and effective. Multiple combinations should be considered of the available resources and the technologies for energy conversion centering on the existing bagasse boiler and power generation system. Sugar production occurs in a limited season of around 4 months from the beginning of December to the middle of the following April. Although the in-house CHP plant utilizes part of the bagasse as fuel during the season for sugar production, it is not currently operated during the off season. In this study, scenarios were generated to utilize unused biomass in the region as fuel for a sugar mill CHP during the off season, when biomass is incinerated at sugar mills or not transferred from the forest in the base case. The excess bagasse is kept for such utilization on-site.

As the alternative scenarios for CHP, we considered the utilization of biomass-derived fuel in local heating by conventional small- and medium-sized distributed boilers or stoves at factories and in residences. These technology options were selected on the basis of criteria regarding whether they could be employed in energy generation using the available resources described below, and whether they had already been developed for practical use.

As well as sugarcane bagasse, the residues of thinning, sawmill, and wood chipping were considered as available resources based on interviews and discussions with the on-site engineers and stakeholders, and following the investigation of available reports about the plan for a biomass town.
in Tanegashima (Minamitane-cho 2008; Nakatane-cho 2009; Nishinoomote-shi 2008). The available amounts of each resource are shown in table 1. For reference, molasses is another by-product of sugar production and is currently used as livestock feed in the island or exported for fermentation. The material flow of molasses was not changed in this study. Though gasification power generation systems are also available, we did not consider these feasible in Tanegashima because of the limited funds and industries.

The system boundary of the scenario analysis is shown in figure 3. The geographical boundary is the whole island of Tanegashima. It is assumed that the targeted biofuels are generated and consumed within Tanegashima; the main products, that is, raw sugar and wood products, are exported from Tanegashima. Existing conventional supplies of energy derived from FFs were included in the boundary as reference systems. The qualities of the energies produced from biomass, that is, heat and power, were carefully checked through consideration of their equivalency with ones from FFs. Sugar production, wood production, and forestry were partially included in the boundary as the producers of residual resources and energy consumers. The life cycles mainly associated with the production of raw sugar and wood products were excluded; namely, sugarcane milling, sugar crystallization, or sawing. This is because the boundary conditions, that is, the amount of sugar and wood products, were the same in all scenarios. The boundary in this scenario analysis starts from the excess by-products from the production of raw sugar and wood products. The energy produced is assumed to be usable by related stakeholders in this scenario analysis as shown in figure 3. The steam and electricity produced are accessible by all energy consumers, for example, the industries of forestry and wood production, or the public. To take into account the above-mentioned qualities of energy produced by biomass and the change in fossil consumption, the energy flows originating from biomass-derived fuels in Tanegashima and GHG emissions based on LCA were examined.

The functional unit for this examination was defined as 1 year of operation of related systems in Tanegashima, because the sugar mill has an on- and off-season for sugar production within 1 year and the behavior of energy consumption varies seasonally. For the scenarios with new construction of facilities, for example, pelletizers, boilers, and district heating pipelines, the lifetimes of constructed facilities are assumed to be 40 years (e.g., CVC 2011). All scenarios use a “functional unit” for the amount of energy consumed and the production of products (e.g., raw sugar, wood products, and their by-products) in Tanegashima. The reference flows for the functional units were adjusted by calculating the environmental loads attributable to the inadequate supply for energy consumption as shown in equation (1).

$$\iota_i = \iota_i^0 + (\max_j P_j - P_i)\varphi_{\text{Elec}} + (\max_j Q_j - Q_i)\varphi_{\text{Heat}} \quad (1)$$

where $\iota_i$ [kg CO₂-eq/FU] is the adjusted environmental load for scenario $i$, $\iota_i^0$ [kg CO₂-eq] is the environmental load with foreground technology options in scenario $i$, $P_j$ [kWh] and $Q_j$ [MJ] are the amounts of electricity and heat, respectively, and $\varphi_{\text{Elec}}$ [kg CO₂-eq/kWh] and $\varphi_{\text{Heat}}$ [kg CO₂-eq/MJ] are the emission factors of electricity and heat production by background technologies, respectively. max $P_j$ and max $Q_j$ are the maximum electricity and heat generation among all scenarios. As shown by the terms (max $P_j - P_i$) and (max $Q_j - Q_i$), the same amounts of electricity and heat are generated in all scenarios with the consumption of electricity from the existing power grid and heat originating in FFs.

### Table 1 Scenario settings for the use cases of available local renewable resources

| Resources (availability [t-wet/yr]) | Pathways | Base | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|-----------------------------------|----------|------|---|---|---|---|---|---|---|---|---|----|----|----|
| Excess bagasse (5,800)            | Incineration \[\text{Cogeneration}\] | ✓   | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓  | ✓  | ✓  |
| Thinning residue (2,180)          | Left in forest \[\text{Chipping} \rightarrow \text{Heat utilization}\] | ✓   | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓  | ✓  | ✓  |
| Sawmill residue, i.e., sawdust and bark (1,660) | Incineration \[\text{Cogeneration}\] | ✓   | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓  | ✓  | ✓  |
| Chipping residue, i.e., bark (2,160) | Incineration \[\text{Cogeneration}\] | ✓   | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | ✓  | ✓  | ✓  |

Note: A check in a cell means that the total available amount of resources are applied, or disposed, through corresponding pathways.

* t-wet/yr = tonnes of wet matter per year.

Kikuchi et al., Industrial Symbiosis in Tanegashima, Japan 279
Scenarios on Biomass-Derived Fuels

Twelve scenarios were defined by combining the pathways of the above-mentioned biomass fuels and heat and power technologies. Based on the previous investigation of the availability and possibilities of unused resources in Tanegashima, the pathways of the utilization of each resource were generated and are shown in table 1. The base scenario is that all resources are left in the forest or simply incinerated with no energy recovery. For other scenarios, pathways of each resource were set as follows. Excess bagasse from the sugar mill is used as fuel for the existing CHP plant at the sugar mill during the off season of sugar production in all scenarios except the base one. Thinning residues are available by removing them from the forest; three pathways were specified for energy generation in this analysis. Sawmill residues are available from the wood production process in the form of sawdust and bark. Chipping residues come from the wood chip factory in the form of bark from the preprocessing of wood chip production. According to our interviews with the experts on local systems in Tanegashima, woody biomass can be utilized as fuel for distributed boilers or for the CHP system at the sugar mill with bagasse. Chipping and pelleting become the pretreatment process for their utilization pathways. Although it is not included in the pathways to CHP plants in table 1, pellets are used in distributed boilers to generate high- or low-temperature steam through a pelleting process. Note that the emissions from soil discussed in life cycle impact assessment are not considered because there is no land transformation or additional land occupation between the base and other scenarios. This is partly because all scenarios adopted existing facilities in Tanegashima.

Modeling for Calculating Inventory Data of Technology Options

The required inventory data were prepared by investigating actual factories and modeling technology options. The data for the sugar mill were extracted from the operation records obtained from the mill in Tanegashima. The specific energy consumption of the wood chipper was taken from the literature (Takanashi et al. 2009). The balance of feed and product was modeled by modifying the equations in Takanashi and colleagues (2009) to consider arbitrary moisture contents of the feed woods. The thermal efficiency of the boilers for wood chips and pellets was based on the study of Yagi and Nakata (2006), and the lower heating values of the biomass-derived fuels were estimated from the analysis by Sekino and colleagues (2011). The background inventory data regarding the production of other materials, transportation, and construction were collected from multiple databases (JLCA 2013; JEMAI 2012; Swiss Center for Life Cycle Inventories 2010).
Results

Energy Flow Analysis of Sugar Mill

Figure 4 shows an overview of flows in the sugar mill. Figure 5 shows the results of energy analysis on the sugar mill in Tanegashima. The total available heat quantity from bagasse was estimated as 295,932 gigajoules per year in the 2012–2013 sugar production year. Of the supplied heat quantity of bagasse excluding “Nonuse as fuel” part (16%) in figure 5a, 54.2% was utilized in processes in the sugar mill. Based on figures 5 and 6, the remaining loss of energy, that is, 45.8% of the supplied heat quantity of bagasse, was as described below. Part of the bagasse was not utilized for fuel, but was mainly used in livestock industries as bedding. It was regarded and included as the loss of bagasse for fuel in the bagasse yard. In Tanegashima, many types of biomass can be used in livestock industries, and large amounts can be available. The substitution of other biomass for bagasse in livestock industries is assumed to be possible in this scenario analysis (see also the Discussion). Bagasse fed to the boiler was burnt for generation of steam at 343°C and 1.85 megapascals (MPa); the steam was transferred to a high-pressure steam header (HPSH). At the boiler and HPSH, some of the heat generated from bagasse was lost at around 43°C to 306°C and 344°C, respectively. After adjusting the pressure and temperature at the HPSH, high-pressure steam was divided into two main streams: power generation and mill turbines. After rotating turbines, the steam flows at decreased pressure and temperature are combined at the low-pressure steam header (LPSH) and the conditions result in 140°C and 0.08 MPa. From HPSH to LPSH, three types of energy losses were observed. A slight loss was found in the power generation turbine, which can be regarded as the energy for heating the turbine materials. Part of the energy was lost at the LPSH while adjusting the pressure and temperature. The energy demand for purification and crystallization may exceed that available in the cascaded steam after power generation and milling. Pressure reducing valves (PRVs) were employed to complement the low-pressure steam, thereby losing some of the energy in the high-pressure steam. From the usage of low-pressure steam in the multiple-effect evaporator and crystallizers, much heat is lost as hot water and low-pressure steam less than 100°C, which are the summation of the water originally contained in the sugarcane and the mixed water in the sugar mill for the maceration of the sugar included in the sugarcane. Approximately 149,000, 6,300, and 8,000 tonnes per year (t/yr) of water were output from the evaporator as hot water and low-pressure steam, and from the crystallizers as low-pressure steam.

Scenario Analysis: Available Energy and Greenhouse Gas Emissions Associated with Industrial Symbiosis

Figure 6a shows the available electricity and heat quantity of steam in each scenario. The electricity and steam from the bagasse boiler are available only during the off season of sugar production, and the value shown in the figure is the total amount during the off season. Available steam is classified in three categories: bagasse-, wood pellet-, and wood chip–derived steam. Wood pellet– and wood chip–derived steam are combined in one bar chart and separated from the one for bagasse-derived steam, because the steam after power generation in the bagasse-derived CHP plant must be utilized quickly in the neighborhood of the sugar mill. Scenario 12 has the largest amount of electricity of all scenarios, where all biofuels are fed into the CHP plant at the sugar mill and produce...
4.19 gigawatts (GWh)/yr of electricity, as well as the largest amount of steam, 106.4 terajoules (TJ)/yr around 140°C. Scenario 5 has the largest amount of steam from wood chip and pellet boilers. Although the heat quantity available in scenario 5, that is, 21.1 and 34.8 TJ/yr from wood chip and pellet, respectively, was smaller than that in scenario 12, the steam in scenario 5 has more flexibility in temperature settings by transporting biofuels and installing appropriate boilers. By focusing on pellet-based heat, scenario 1 produces the largest amount of steam from pellets, 53.5 TJ/yr. Considering the stabilization of the heat quantity of pellets by pelleting rather than wood chipping, scenario 1 may be preferable if specific heat demands require strict energy management.

Figure 6b shows the GHG emissions in all scenarios considering the differences between renewable resources or non-renewable ones. The reference flows of electricity and steam were set as their largest amounts generated in all scenarios; 4.19 GWh/yr of electricity and 106.4 TJ/yr of steam in scenario 12. The amounts of steam from wood chip boilers in scenarios 5 to 8 (21.1 TJ/yr) were adopted because all these scenarios have the same value. The amount of steam from pellet boilers in scenario 1 (53.5 TJ/yr) was adopted. All scenarios must generate the same
amount of electricity and steam even if additional FFs are required to meet this condition. For example, scenario 12 has the same amount of electricity and steam from the CHP plant as the reference flows, but it has no steam with the same qualities as that from wood chip and pellet boilers. Therefore, additional FFs are consumed to meet the steam requirements. Based on these conditions, the scenario with the smallest amount of GHG emissions in all scenarios was scenario 12, at $5.87 \times 10^6$ kilograms (kg) carbon dioxide equivalent per year.

**Discussion**

A revitalization of local rural areas has become an issue in our aging society (Komiyama 2014), and the establishment of a robust energy system in a region with locally available resources can be a solution for these emerging issues and should be addressed when thinking about symbiosis (Komiyama 2014). The scenario analysis demonstrated that the system examined in this study has the potential to produce additional energy in Tanegashima. To sustain the system, its robust contribution to the local area and the stability of its supply/demand structure should be adequately achieved; otherwise, the technology implementation would not be accepted by the local community. The power and heat supply/demand structures and the indirect effects by implementing the new system were discussed below.

**Power Supply and Demand**

Biomass-fired power plants can be a solution for mitigating the shortage of load-following capacity in micropower grids such as in Tanegashima. The power mix has a large impact on GHG emissions attributable to the use of electricity (Marriott et al. 2010). Renewable power generation technologies with an instability in the power supply, such as photovoltaic (PV) and wind turbine (WT) power generation systems, can reduce GHG
emissions. Some electric power companies, however, have begun to refuse new installations of PV and WT systems interconnected with their local power grids (e.g., Kyushu-EPCO 2014). This is because of the limited load-following capacities of power grids. Since the earthquake in 2011, Japanese people have become very sensitive about the safety and stability of the power supply. The public electricity in Tanegashima is currently generated and supplied by two power plants on the island with capacities of 24,000 and 16,500 kilowatts (kW) belonging to Kyushu-EPCO. Because the power grid of the island is not connected with the main power grid in Kyushu, all the electricity in the island is currently supplied by these two power plants (see also table S2 in the supporting information on the Web). Their power generation efficiencies and operation ratios are approximately 38.2% and 39.0%, respectively, according to Kyushu-EPCO (2012). Because of the cost of transporting FFs to these remote islands, power generation utilizing them has become expensive. Based on these conditions, the power company has a good incentive to accept power generation utilizing local biofuels as a new power plant in Tanegashima.

As shown in figure 6a, scenario 12 has the largest amount of electricity, 4.19 GWh/yr from biomass-derived fuels during the off season of sugar production, and this corresponds to approximately 724 kW of power capacity. The profile of annual power generation comparing the on and off season of sugar production is shown in figure 7a. If all of the generated power is consumed during the off season, it amounts to approximately 2.7% of the annual power generation in the island, based on records from 2011. Considering the daily load curve (see figure S4 in the supporting information on the Web), the power generation can be controlled to enhance the load-following capacity of the electricity grid. Figure S5 in the supporting information on the Web shows the power supply curves considering the daily power-load curves in figure S4 in the supporting information on the Web.

The possible power supply around peak time is around 1.12 megawatts (MW), which is approximately 4% of peak demand (28.3 MW in 2011). Biomass-derived power generation can be an option to increase the load-following capacity of the power grid as well as an energy source from renewable resources. In Tanegashima, the possible reduction in the power supplied by internal-combustion power generation can be increased from 7.02 to 8.14 MW, a 16% improvement. Note that in figure S5 in the supporting information on the Web, the power supplied from the CHP plant at the sugar mill is decreased compared with figure 7a during the month when the power demand is low.

**Heat Supply and Demand**

In addition to electricity, heat is an important energy available from biomass with relatively low GHG emissions (Cherubini and Strømman 2011; Muench and Guenther 2013). According to Guest and colleagues (2011), the heat from CHP has low GHG emissions where the allocation was based on the exergy of the products. In our study, the environmental performance was quantified by defining [U] to include both electricity and heat. Figure 7b shows the quality of available heat from the CHP plant at the sugar mill. Although the quantity of heat [J] has been generally discussed for high- or low-temperature heat demand in the field of LCA, the temperature [°C] and thermal power capacity [W] are also taken into account in this study. In other words, the quality of generated heat is examined carefully. The three main types of available heat in this study are discussed below. Each heat supply has different temperature, temporal and spatial availability, and usability on storage. Although the GHG emission levels of these pathways are examined in figure 6, selection of pathways should be considered on the basis of the match between actual demand and the characteristics of affordable energy in these pathways. The characteristics and considerations for the utilization of each type of heat are summarized as follows.

Exhaust heat from the sugar mill during the sugar production period corresponds to part of the heat losses that were quantified in the energy flow analysis of the sugar mill shown in figure 5. The temperature of the exhaust heat ranges can be grouped as shown in figure 7b into a low-temperature group (<100°C) and a high-temperature group (around 350°C). Although they do not have enough exergy to generate power or rotate large devices, such as mill turbines, they can meet the demand for low-quality heat, for example, dehydration by simple evaporation, hot water, or prewarming of bagasse or other biomass-derived fuels. Protected horticulture, for example, requires heat to maintain temperatures inside the growing houses (Kozai 2013). The low-temperature heat can be applied into this field. At that time, adsorption/absorption chillers (Kato et al. 2010) may also be needed to produce cold heat by using warm heat as combined heat, power, and cold, so-called trigeneration.

Low temperature steam after power generation is available during both the on and off season of sugar production from the CHP plant, which is at 140°C and 0.08 MPa. Scenario 12 has the largest amount of heat (106.4 T/yr) from steam production during the off season. An important demand for this heat may be from the drying process in the sawmill. The quality of the product wood is greatly affected by the drying process, which takes the moisture content of the wood from 30% to 200% to 10% to 25% (dry wood base, i.e., containing a certain amount of water [kg-water content] per unit of wood dry matter [kg-dry matter content]) and requires large amounts of heat at around 150°C. Steam from the bagasse boiler or low-temperature exhaust heat is also applicable in other industries for boiling water, heating ingredients, or drying products. The other option to utilize the steam is district heating. The difficulty in installing district heating is that it requires the construction of new heating pipelines in the area. The nearest city to the CHP plant is 4 kilometers away. It is preferable to attract industrial consumers that have stable and predictable heat demand. Pipeline or other heat transfer technologies (Chan et al. 2013) can be applied into such symbiosis.

Heat generated by wood chip and pellet stoves or boilers can be used at public facilities or industrial factories. Their
Figure 7  Characteristics of additionally available energy derived from local renewable resources utilizing the existing bagasse cogeneration system. The amounts of available energy during the off-season period were based on the results of scenario 12, which has the maximum power generated by available resources: (a) profile of power generation from CHP plant at sugar mill. If the power demand in September is higher than October, the periodic maintenance can be rescheduled from September to October; however, the schedule must not inhibit sugar production, the season of which is controlled by the maturation of the sugarcane. (b) Quality of available heat and attainable range on demand side.

transportation can be achieved using the return runs of trucks delivering sugarcane or lumber. For distributed CHP from wood chips and pellets, small-scale CHP systems have been studied (Nakanishi and Ogi 2005). These distributed systems may be useful for supplying heat and power from wood chips and pellets instead of conventional fossil-derived stoves and boilers, which sometimes have large exergy losses. For example, the production of hot water requires lower-exergy energy than power generation.

Symbiosis in Tanegashima with Local Resources

Industrial ecology research can be applied to the specifications to obtain useful insights and actionable recommendations for islands (Eckelman et al. 2014). IS is necessary for the design and analysis of island systems, which have been conducted but remain mostly undocumented (Krausmann et al. 2014). CHP can become a technology enabling the substitution of local resources for FFs (e.g., vehicles based on woody biomass; Singh et al. [2014]). To achieve high efficiencies of resource utilization
with CHP technologies, the matching of heat/power ratios between energy demand and supply should be carefully addressed, whereas many state-of-the-art technologies have been developed for increasing only power generation (Koyama et al. 2014). CHP technologies have specific heat and power ratios based on the type of technology and its scale (Kikuchi et al. 2014, 2015). The demand-side ratio may change if the sectors or subsectors are mixed and share CHP plants as distributed energy sources. For example, cooperation among residential, commercial, and industrial sectors can change the heat/power ratio because of their different profiles of energy demand (Kikuchi et al. 2014, 2015). Combining the sectors as not just “industrial” symbiosis, but also as symbiosis in all Tanegashima, the local renewable resources can be highly utilized to supply local energy requirements with less use of fossil resources from outside the region. At the same time, energy symbiosis can strengthen the business robustness of the primary industries as well as their industrial competitiveness with by-product energy. For example, potatoes rotated with sugarcane, which is the raw material for starch production, can be strongly supported by generated power and heat through symbiosis. Sugarcane can have deleterious effects, such as the decrease of yield or the increase of harmful insects, on its growing when it is cultivated on the same ground in consecutive years (Ambrosano et al. 2013). The cultivation of potatoes in Tanegashima avoids such deterioration of sugarcane yield effectively. The support of starch production may stabilize the agricultural cycles. This is regarded as an indirect effect by establishing symbiosis over agricultural and industrial processes.

Excess bagasse is currently used for bedding for bulls or as raw material for composting in Tanegashima. Both usages support other important industries. Whereas substitutes for bagasse must be found if it is preferentially used for energy use, the amount of excess bagasse has thus far greatly exceeded such demands. The results in the scenario analysis show the potential of bagasse for energy use in Tanegashima. These results may motivate the use of new types of sugarcane, such as a high-yielding one with new sugar production technology to increase both sugar, ethanol, and thus bagasse by removing reducing sugars from cane juice (Ohara et al. 2012). Feeding-type sugarcane can increase feeds for cows (Sakaigaichi and Terajima 2008; Sakaigaichi et al. 2010), resulting in the increase of composts through livestock excretion. Bark from woody biomass production increases for the bed of bulls instead of bagasse. Because the bagasse generated in the sugar mill does not require additional transportation, it has advantages in energy use. High-yielding sugarcane can be utilized for sugar production with the support of selective fermentation and can generate more excess bagasse. For use in livestock industries, other types of sugarcane cultivation should be considered. Such a change of agricultural technology options can be effectively implemented under the energy systems proposed in this study.

Conclusions

IS centered on existing bagasse-derived CHP generation plants in Tanegashima was examined through detailed investigation of the plants and scenario analysis of the energy-use pathways of available biomass-derived fuels. The energy flow analysis of the thermodynamic characteristics of an existing sugar mill plant revealed the existence of unused excess energy derived from bagasse, which has high enough quality to meet energy demand in other plants as well as generating additional power. This is partly because some renewables have been regarded as waste in production processes of foods or other high-value-added products. The integrated use of locally available woody biomass, such as residues of thinning, sawmills, and wood chipping, enabled year-round cogeneration by a bagasse-derived energy system and additional steam supply for other energy demands. During the off season for sugar production, the power from the bagasse boiler and power generation plant can supplement the power grid of Tanegashima to increase its load-following capacity when interconnecting additional PV or WT sources. The cogenerated thermal power can also support other industries within Tanegashima.

IS has the potential to facilitate the flexible and strategic utilization of locally available biomass-derived fuels. The cascaded use of heat from power generation for low-temperature heating can increase efficiency of utilization of resources. In the installation of CHPs, the power-to-heat ratio should be designed on the potential demand to increase their operation ratio. In particular, the temporal and spatial gaps in heat supply/demand must be addressed. This is partly because the conversion efficiency of power from fuel content heat cannot easily reach above 60%, even at a maximum, and a large part of the heat from fuel is lost as just heat. In-house energy plants already installed in some industries can become decentralized regional energy centers supplying power and heat to their local area. Then not only fuels conventionally utilized in these energy plants, but also locally available biomass can be co-combusted in the CHPs as fuel to reduce GHG emissions. A CHP installation using local biomass may allow the sustainable installation and operation of factories processing plant-derived renewable resources as a kind of integrated generation of high-value-added products, such as foods, and materials as well as electricity and thermal power.

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Supporting Information

Additional Supporting Information may be found in the online version of this article at the publisher’s web site:

Supporting Information S1: This supporting information provides an overview of available renewables in Tanegashima, with basic information on the island and on the sugar mill in Tanegashima. The estimated daily power load curve in Tanegashima is also shown.