Distributed Cogeneration of Power and Heat within an Energy Management Strategy for Mitigating Fossil Fuel Consumption

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Introduction

Distributed energy sources, such as self-power generation plants in industry, are used in fuel-to-energy conversion technologies according to the demand from their respective manufacturing processes (e.g., Chicco and Mancarella 2009).

These energy-supplying technologies located within demand-side sectors can be used as highly efficient energy supplies when considering the actual specifics of the relevant energy demand. At the same time, distributed energy systems, such as combined heating and power (CHP) or combined cooling, heating,
Table 1: Abbreviation and nomenclature

| Abbreviations | Expansion of abbreviation |
|---------------|---------------------------|
| AME           | Africa and the Middle East |
| AS            | Developing Asian countries |
| C             | A coefficient depending on the number of engine cylinders required [-] |
| CCHP          | Combined cooling, heating, and power |
| CHP           | Combined heating and power |
| CN            | China |
| CRGT          | Chemically recuperated gas turbines |
| DE            | Diesel engine |
| div           | Divisions |
| EIT           | Russia and other economies in transition |
| EUR           | Europe OECD |
| FuelC\textsubscript{elec} | Consumption of fuel as electricity in division div |
| FuelC\textsubscript{heating} | Consumption of fuel as heating in division div |
| GCC           | Gas combined cycle |
| GHG           | Greenhouse gas |
| GE            | Gas engine |
| GT            | Gas turbine |
| IEA           | International Energy Authority |
| IN            | India |
| IRP           | International Resource Panel |
| LA            | Latin America |
| LC-GHG        | Life cycle GHG emission [kg CO\textsubscript{2}-eq/functional unit] |

\(n\) Rotation speed of engine [min\(^{-1}\)]

| Abbreviation and nomenclature | Expansion of abbreviation |
|------------------------------|---------------------------|
| NA                           | North America OECD |
| PAC                          | Asia OECD |
| PEFC                         | Polymer electrolyte fuel cell |
| SOFC                         | Solid oxide fuel cell |
| UNEP                         | the United Nations Environment Program |
| \(W_{\text{DEG}}\)          | Weight of steel in an engine [10\(^3\) N] |
| \(W_{f}\)                    | Weight of cement [10\(^3\) N] |
| \(\alpha\)                  | Vibration-proof coefficient of engine [-] |

Note: OECD = Organization for Economic Cooperation and Development; kg CO\textsubscript{2}-eq = kilograms carbon dioxide equivalent; N = newton (kg m/s\(^2\)).

and power (CCHP) systems (table 1), have the potential for upgrading the resiliency of an energy system (McLellan et al. 2012), as seen during recent devastating natural disasters, such as the Great East Japan Earthquake (Fukushima et al. 2011). In addition, distributed energy systems have the potential to reduce emissions by sharing excess heat when used in district heating systems (Gebremedhin 2012), or by increasing energy efficiency from increased utilization (Çomaklı et al. 2004). Based on the existing roadmap for cogeneration systems (Kikuchi et al. 2014), these systems have the potential to increase the utilization efficiency of resources through their implementation in commercial, residential, and industrial sectors.

The power-to-heat ratio of cogeneration technologies must be considered carefully to meet local energy demand. In particular, the demand for heat should be addressed when planning the utilization of these systems. This is because there are temporal and spatial gaps in the supply/demand of heat, whereas any electricity generated can be utilized by the public through the existing infrastructure (METI 2014). Industrial symbiosis (IS) is an effective method for balancing the supply/demand of energy to the regional community (Chertow 2007) and has the potential to increase the uptake of CHP plants in the public energy system (Koyama et al. 2014), considering the quantity of energy required (in joules [J] or watts-hours [Wh]), and also the quality of energy required, such as the temperature of the heat supplied (in °C).

For example, industrial boilers can generate high-pressure steam at temperatures above 500°C, and the temperature can decrease to, say, around 150°C after using the steam to generate power in a steam turbine. Considering the efficiency of heat exchangers, this steam may be then usable as a heat stream for meeting heating demand for temperatures below 120°C, for example, for water separation in a distillation column. A lower temperature steam may require a longer residence time for heating colder streams than for higher temperature streams. So far, there has been little attention paid to using such relatively lower temperature streams for heating. However, many processes have a heat demand below 100°C. Such lower temperature streams may be used to meet this type of demand more effectively than higher temperature streams, thus allowing a more efficient utilization of resources. As well as the power-to-heat ratio of the energy generated by distributed energy sources, the temperature of the steam needs to be adjusted for the demand-side conditions.

An effective energy management strategy in the demand-side sector needs to be able to address the planning of distributed energy sources for mitigating the consumption of fossil fuels and the emission of greenhouse gases (GHGs) (table 1). The reduction of exergy losses through the matching of energy supply/demand can lead to an increase in resource utilization efficiency. Because not all energy can be converted into electricity, the cascading use of generated energy from the primary energy source may become effective by distributing the right technologies to the right places considering the characteristics of technologies, actual energy demand, operation records, and the relationship with current energy systems.

This article was written in conjunction with a series of reports by the United Nations Environment Program (UNEP) International Resource Panel (IRP) that quantify and compare the environmental and natural resource impacts and benefits of using demand-side efficient technologies for GHG mitigation scenarios from now until 2050. In this article, we characterize the existing distributed energy technologies and examine the potential of using cogeneration or multigeneration technologies to penetrate existing local energy supply networks. After defining the cascading use of energy in this study, three types of analyses are conducted in the examination of the current status and future possibility of cogeneration technologies (see also Figure S1 in the supporting information available on the Journal’s website). A critical review of the current status of research on distributed energy technologies was conducted using a bibliometric analysis allowing visualization of the citation networks of related research. The main keywords on available technology options for distributed energy sources are critically
reviewed through bibliometric analysis. Considering the specified concerns about technologies, information on actual technology operations was collected from a wide range of sources, and the data were scrutinized in addition to an examination of the literature and interviews with engineers at actual plants. The effect of installing distributed energy was analyzed based on a scenario analysis of technology options, where a model is developed from the collected operation records. Based on a life cycle inventory (LCI) analysis of a cogeneration plant using existing databases, for example, ecoinvent v2.2 (Swiss Center for Life Cycle Inventories 2010), the advantages and disadvantages of distributed energy technologies are discussed.

Methods

Heat Quality within Cascade Energy Usage

As shown in the conceptual diagram in figure 1, a cascading use of energy contained in fuel considers the quality of energy and enables a highly effective use of resources. Any remaining energy can be lost as waste heat from devices such as fuel cells, gas engines (GEs), diesel engines (DEs), or gas turbines (GTs) (table 1). This waste heat has a high enough temperature for use in other applications. Some waste heat can be utilized by boilers to generate steam, which can then be used to generate electricity, such as in gas combined cycle (GCC) power generation plants. In addition, most of the heat demand in the commercial and residential sectors, such as for regional heating, hot water, or ambient heating/cooling, can also be met using the waste heat from power generation (see, e.g., The Energy Data and Modeling Center, The Institute of Energy Economics, Japan 2013; Koyama et al. 2014). However, there are many potential combinations of technologies, and an incorrect combination may not be beneficial, resulting in a low operation ratio, excess unusable heat, and a low resource utilization efficiency. An examination and analysis of the available technologies and actual energy demand needs to be carefully conducted in considering the possibility of using cascade energy. This will enable enhancement of IS, elimination of energy loss, mitigation of fuel consumption, and the clarification of potentially applicable technologies for production.

Review and Modeling of the Technology Options for Distributed Energy Sources

Bibliometric Analysis of Cogeneration

Citation analysis, a type of bibliometric analysis, was conducted to determine the research activity on distributed energy technologies. Bibliometrics is a commonly used method for characterizing academic fields based on published literature, for example, an analysis of the evolution of IS by Yu and colleagues (2014). The academic landscape system (Innovation Policy Research Center 2013; Kajikawa et al. 2007) was adopted as a method of characterizing research into distributed energy technologies. This has been applied previously to the characterization of sustainability (Kajikawa 2008), its assessment methods (Kikuchi 2014), and to energy security (Kiriyama and Kajikawa 2014). We retrieved 1,493 articles from a Web-based literature database, “Web of Science” (Thomson Reuters 2014), which included “cogeneration,” “trigeneration,” or “coproduction” in the abstract, title, or keywords, and we created clusters arranged from these citation networks. The detailed procedure of the retrieval of articles, the analysis of citation networks, and the creation of clusters has been discussed in previous works (e.g., Shibata et al. 2009; Kiriyama and Kajikawa 2014). By characterizing the research activity related to distributed energy generation, the bibliometric analysis facilitates a sophisticated understanding of the points and options to be considered for utilizing cogeneration in energy management.

Analysis of Current Energy Demand in the Industrial and Commercial Sectors

In addition to the bibliometric analysis, two types of information were collected and analyzed: actual process information about the required heat quality, especially the temperature, and statistics on energy consumption in the industrial and commercial sectors. The penetration of distributed energy technology in power grids is based on the various countries’ statistics whereas the required amount of energy in industrial and commercial sectors is only for Japan given that the source is Japanese statistics. Process information about the heat quality was extracted from the existing literature on manufacturing processes, mainly focusing on the chemical industry (e.g., SCEJ 1970) or other industries that have been investigated in detail (e.g., Kikuchi and Hirao 2010; Kikuchi et al. 2011) and through interviews and discussions with actual manufacturers. Production processes often have multiple temperature requirements, for example, bioethanol production using fermentation has unit operations around 45°C (for fermentation) and 100°C (for the dehydration of ethanol to form 99.5% ethanol using azeotropic distillation). Because these unit operations are commonly used all over the world, there was sufficient consistent data. Therefore, in our analysis, these unit operations were counted and examined separately.

The sectors targeted in this study were classified based on the categorization of industrial and commercial divisions, as shown in table 2. The quality of the heat requirements was assessed using this process information, and then the quantity of heat requirement was examined using statistics. Japanese statistics (METI 2014) were applied to analyze the energy consumption in the industry subsectors in detail, and the data were converted into energy rankings for sectors that could be supplied using additional distributed energy sources. In the statistics, the nonenergy used resources, for example, naphtha for chemical production in Japan, are also included. The actual energy pathways for meeting energy demand were examined to show the usage of electricity from the public power grid and from off-grid sources (e.g., as steam, hot/cold water, raw materials, and low temperature heating). The current supply from conventional distributed energy sources was estimated, and the efficiency of power and heat conversion in distributed energy sources was calculated using the models discussed in the next section.
Figure 1 An illustration of the usage of cascade energy contained in fuel. Fuel contains a chemical potential energy that can be converted into various forms, such as thermal, physical, electrical, and magnetic energy through appropriate converters, such as combustors, boilers, or turbines. Thermal and electrical energies are considered the major energy types of interest in general, the quality of which is represented as the temperature of the thermal energy generated. Relatively high temperatures, or degree of quality, are required to generate electricity, and all the potential energy contained in the fuel cannot be converted into electricity. Rectangles indicate technologies, dotted rounded rectangles indicate sets of technology options to be compared, and ovals indicate materials or information.

Finally, the quantity of heat required that could potentially be supplied by additional distributed energy sources was assessed. In addition to the space required for distributed energy sources in industrial and commercial sectors, the penetration (i.e., the proportion in the power mix) of power from distributed sources in the energy conversion sector was also examined based on data extracted from international statistics (e.g., IEA 2015; EC 2015). Through our analysis, the current energy supply in the industrial and commercial sectors was characterized based on the available sources of energy. For example, electricity can be provided from the power grid or from a self-powered generation plant, and the heat required can be supplied through cogeneration or a boiler/furnace.

Modeling of Cogeneration for Distributed Energy Sources

Some power generation technologies have a scale factor, which means that the performance, or inventory (process input/output or life cycle inventory), of a technology is dependent on its power generation capacity. The actual installed capacity can be strongly related to the quality and quantity of the expected energy demand. Available fuel resources also have an influence on the selection of a particular technology. Technology models are required in order to examine which technologies are adequate for specific energy demands. Actual operational records (e.g., Ecofys 2010; Hirata 2012; Miura 2004) and predicted values of the scale factors were collected in this study to address the performance of technology installations quantitatively, including the appropriate scale factors mentioned above. After basic statistical analysis methods were applied, the performance of each technology was then evaluated in terms of the power conversion efficiency and the mass of steel and cement required to install the distributed energy technology adopted. For example, the weight of steel used in an engine, $W_{DEG}$, was calculated by summing the weight of each of the components in the engine using the values published by the manufacturer (ACEUC 2000) (table 1). The weight of cement, $W_f$, was calculated using the formula revised from Maleer’s experimental formula (MLIT 2012), which is employed by the Yanmar Co., Ltd. (Sunyou 2014) (table 1). Equation (1) was used to calculate these values for GE and DE, and equation (2) was used to calculate these values for GT:

$$W_f = C \cdot W_{DEG} \cdot n^2$$

$$W'_f = \alpha \cdot W_f$$

where $W_f$ is the weight of cement for a GE or DE with a given capacity of power generation (in units of $10^3$ N), $W_{DEG}$ is the weight of steel in an engine (in units of $10^3$ N), $n$ is the rotation speed (min$^{-1}$), $C$ is a coefficient that depends on the number of cylinders required (dimensionless), for example, for six in-line with a V-12 cylinder ($C = 0.17$) or for 3, 4, 5, and 8 in-line with a V-16 cylinder ($C = 0.20$), $W'_f$ is the weight of cement used in a GT ($10^3$ N), and $\alpha$ is the vibration-proof coefficient (dimensionless), which had values in the range 0.2 to 0.4, and in general, has a value of 0.4 during the planning phase of a power generation plant.
Scenario Analysis for Distributed Energy Sources

Based on the developed models that were employed in the estimation of power conversion efficiency and the required amount of cement and steel, the effect of the installation of distributed energy sources was investigated. The details of the technologies examined are shown in Table S1 in the supporting information on the Web. Because of the differences in power generation efficiency, a variety of technologies with different power generation capacities were examined using scenarios in this study. The data on power generation technologies are general, even though the raw data were collected mainly from Japanese companies that export their products and technology to other countries. In addition, these companies have many competitors all over the world that produce similar products. Therefore, the technology-specific data, such as the power conversion efficiency and the required mass of steel or cement dependent on its capacity, can be used for analyses in other countries as well. GTs, DEs, and GEs were selected as suitable technologies to analyze the future requirements for power generation, and, in addition, chemically recuperated gas turbines (CRGT) (Abdallah and Harvey 2001) were also considered in this study. CRGT is an applicable technology for distributed small- to medium-sized GTs (Nakagaki et al. 2003). It has been demonstrated empirically that CRGT can improve the efficiency of GT power generation by approximately 10%. Power generation values of 200 kilowatts (kW), 1 megawatt (MW), and 10 MW were set as representative scales for distributed energy sources. The technological settings for cogeneration systems were extracted from the literature or from corporate catalogs of equipment in regular use in Japan (e.g., Kawasaki Heavy Industries Ltd. 2014; Yanmar Co. Ltd. 2014).

Cogeneration systems have two different products (heat and power) produced in two types of installations (heat- and power-oriented installations). In heat-oriented installations, the heating demand, for example, 1 megajoule (MJ) of heating, is replaced by cogenerated heat with the electricity being generated as a by-product. In this regard, both heat and power are assumed to be consumed without any additional infrastructure, except for power conditioners for selling electricity to the grid. On the other hand, if cogeneration technologies are installed using a power-oriented policy, then heat-sharing mechanisms are necessary, whereas any electricity generated would be consumed easily. This is because heat can be lost easily if there is a temporal or spatial gap in the heat demand/supply. Although heat storage technologies have been developed (Chan et al. 2013), this study assumed that the cogeneration technologies would be installed based on a heat-oriented policy.

The impact of a technology is dependent on the conditions that prompted the installation of the technology as well as the background conditions of the installed system technologies. The material inventories for construction and fuels required to run the technologies should also be considered. In particular, the LCI for the power grid may have a strong influence on the final impact. In this study, we selected the following target countries for analysis: China (CN), India (IN), Europe OECD (EUR), North America Organization for Economic Cooperation and Development (OECD) (NA), Asia OECD, that is, Japan/Korea/Australia (PAC), Russia, and others (economies in transition [EIT]), Latin America (LA), developing Asian countries (AS), and Africa and the Middle East (AME). An existing, external model was adopted for calculating the cumulative energy production using cogeneration technologies. This model was constructed for a UNEP IRF special report on the environmental implications of electricity supply technologies (Hertwich et al. 2014). The electricity mixes for 2010, 2030, and 2050 follow the International Energy Authority (IEA)'s Blue Map (GHG mitigation) and baseline (business as usual) scenarios as outlined in the Energy Technology Perspectives (IEA 2010). ecoinvent v2.2 data were incorporated within this model, enabling analyses with region-specific data on cumulative LCIs for the power grid in each area. As for the impact factors on GHG effects, the factors containing the values for fugitive emissions from coal and gas extraction (Burnham et al. 2012) were adopted.

Results

Bibliometric Analysis

Bibliometric analysis revealed that strong relationships exist between cogeneration, exergy loss, biomass, and system optimization in the research literature. Figure 2 shows the schematic results of the bibliometric analysis on cogeneration, represented as a clustering map of the citation networks (see also the Supporting Information on the Web). In total, over 1,400 articles were involved in this clustering.

The largest cluster (Cluster 1) consisted of articles where multigeneration, such as CCHP, was discussed (e.g., Chicco and Mancarella 2009). Cluster 2 used exergy as an indicator to discuss the quality or applicability of energy (e.g., Rosen et al. 2005). Fuel cells are an important technology for use as a resource that has a high conversion efficiency and were evaluated in Cluster 3 (e.g., Parise et al. 2008). Plant-derived resources (i.e., biomass) can be a resource for cogeneration with low environmental impact (Guest et al. 2011). Although various sources of biomass were considered in Cluster 4 (e.g., Mujeeb et al. 2009, 2011), the use of bagasse has been discussed the most (e.g., Ram and Banerjee 2003). Multigeneration requires an elaborate operation scheduling and support system for actual implementation. Such operation of multigeneration plants was considered in Cluster 5 (e.g., Salgado and Pedrero 2008). In Cluster 7, the modeling and optimization of cogeneration was considered from case studies, for example, the application of cogeneration in the industrial sector (e.g., Roy 2001). The application of cogeneration in buildings was also considered using life cycle assessment (LCA) (e.g., Osman and Ries 2007). In Cluster 9, the economic or political aspects of multigeneration technologies were examined (e.g., Wickart and Mdltenor 2007). Gas turbines are a major technology for power generation and are discussed in engineering terms in Cluster 10 (e.g., Wang and Chiou 2004). Their applicability is
discussed in Cluster 11, where the combination of micro-GT and absorption for CCHP was considered (Bruno et al. 2009).

The rationale for analyses of current energy demand, modeling, and scenario analysis are supported by bibliometric analysis. As shown in figure 2 and Table S2 in the supporting information on the Web, multigeneration can be regarded as an important function of distributed energy sources. This is because a cluster requires sufficiently significant differentiation from other topics (Kajikawa et al. 2007), highlighting the clusters that indicate important topics in discussing multigeneration technologies. The increase of resource utilization efficiency can become a target of cogeneration, as discussed in the cluster of exergy and optimization. As with the clusters, the patterns in the keywords identified through the bibliometric analysis indicate the key topics that should be investigated in an analysis of distributed cogeneration. GEs, DEs, and GTs are included in the frequently utilized keywords of analyzed articles. The ratio of power and heat generated from technology or the capacity scale of power generation are also commonly utilized keywords.

**Current Energy Demand**

The actual process information collected was organized as a frequency analysis and a map of the required process temperature was constructed, as shown in figure 3 and figure S5 in the supporting information on the Web, respectively. As shown in figure 3, units operating between a temperature of 50 and 100°C had the highest frequency. Heating demand below 100°C can be met by low-pressure steam, which is often released directly into the environment as waste heat and is not used. In the plants where much heat is consumed, such as in chemical plants belonging to the classification group E16, such low temperature heating demands have been addressed by heat integration, mostly within the plant. For other plants without enough heat sources available, such as food-processing factories in classifications E9 or E10, fuel is required to provide heat, even though there is much exergy loss from fuels for low temperature heat. For classification E9, food industries, and classification E10, beverage and feed industries, temperatures between 50 and 100°C had the highest frequency, as shown in figure 3. In this regard, large amounts of waste heat in the sawmills in category E12 originated in the utilization of sawdust or other residues as fuel. In a sawmill, heating between 100 and 150°C is necessary, which results in the output of waste heat around 100°C. This means that the heat demand in such industries can be addressed through IS with industries having significant quantities of higher-temperature waste heat, as shown in figure 3, for example, from chemical industries, energy conversion, or other heavy industries. From an investigation into actual plants, moreover, a case for IS between sawmill and feed industries exists. Although the waste heat from sawmills is not of very high temperature, it has been utilized in other industries. Such a symbiosis can work effectively for resource saving, as shown by the frequency analysis in figure 3.

In middle temperature ranges from 200 to 400°C, chemical processes, such as distillation utilize heat, and some food industries require some heat in this temperature range. For temperatures above 400°C, the type of industries with heat
demands changed to production processes of anhydrous products. In category A2, charcoals are produced at temperatures around 500°C. Iron and steel, ceramics, and nonferrous metals are produced at temperatures around 1,000°C. In some chemical processes, reactions also require high temperatures, for example, naphtha-cracking reactors require temperatures above 700°C. For this type of heat demand, a form of direct heating is used, such as a furnace, because forms of indirect heating, such as steam, cannot be employed. Through the use of heat exchangers, waste heat may be recovered as steam and utilized in other processes.

Figure 4 shows the potential for energy to be supplied by cogeneration in the subdivisions of the industrial and commercial sectors in Japan. Although the ease of utilization of energy from cogeneration is case specific, in general for buildings that have already installed central heating or cooling systems it is much easier to utilize energy from cogeneration. In some subdivisions, cogeneration systems have been installed and utilized for energy supply (see also figure 6 and figure S6 in the supporting information on the Web). The values in figure 4 identify the energy that is not currently being supplied by existing cogeneration systems. As shown in figure 4a, some industrial manufacturing processes in Japan do not have much energy supplied by cogeneration technologies, whereas the energy demand of industrial processes is relatively higher than that of commercial sectors (see also Figure S6a in the supporting information on the Web). This is because the industrial sector already has more installed distributed cogeneration technologies compared with the commercial sector. In other words, the commercial sector has the potential to install cogeneration systems and reduce resource consumption. The power-to-heat ratio must be addressed carefully. For example, sector I, retail, mainly requires electricity, the power-to-heat composition of which is 93.8% in figure 4b, and it seems that sector I has a large potential for its energy to be supplied from cogeneration according to figure 4a. The ratio of power and heat can be calculated using the data shown in figure 4 (equations 3 and 4):

\[
\frac{\sum_{\text{div}} \text{FuelC}_{\text{elec}}}{\sum_{\text{div}} \text{FuelC}_{\text{elec}} + \sum_{\text{div}} \text{FuelC}_{\text{heat}}} = 0.644 \tag{3}
\]

\[
\text{Average}_{\text{div}} \left( \frac{\text{FuelC}_{\text{elec}}}{\text{FuelC}_{\text{elec}} + \text{FuelC}_{\text{heat}}} \right) = 0.742 \tag{4}
\]

where div denotes the divisions listed in table 2, and FuelC_{elec} and FuelC_{heat} denote the consumption of fuel as either electricity or heating in division div, respectively (table 1). If a division’s power-to-heat ratio is high, it means that cogeneration technologies may not be able to supply all the electricity required without excess heat also being supplied by cogeneration.

Figure 5 shows the installed capacity of cogeneration in residential, commercial, and industrial sectors using the ratio of CHP to public power generation in a range of countries. Larger countries have larger installed capacity of cogeneration.

**Modeling of Cogeneration Technologies**

Figure 6 shows the power conversion efficiencies of applicable cogeneration technologies based on the available operational results. The results of our regression analysis are presented in Table S4 in the supporting information on the Web. The performance level of GE, DE, GT, and ST is dependent on the technology of companies that produce or...
Table 2 Industry classifications used in this study based on the standardized categorization of the Ministry of Internal Affairs and Communications, Japan

| No. | Classified Industry                                       |
|-----|----------------------------------------------------------|
| A1  | Agriculture                                               |
| A2  | Forestry                                                 |
| B   | Fishery                                                  |
| C   | Mining and quarrying of stone and gravel                 |
| D   | Construction                                             |
| E9  | Manufacture of food                                      |
| E10 | Manufacture of beverages, tobacco, and feed              |
| E11 | Manufacture of textile mill products                     |
| E12 | Manufacture of lumber and wood products, except furniture |
| E13 | Manufacture of furniture and fixtures                    |
| E14 | Manufacture of pulp, paper, and paper products           |
| E15 | Printing and allied industries                           |
| E16 | Manufacture of chemical and allied products              |
| E17 | Manufacture of petroleum and coal products               |
| E18 | Manufacture of plastic products, except otherwise classified |
| E19 | Manufacture of rubber products                           |
| E20 | Manufacture of leather tanning, leather products, and fur skins |
| E21 | Manufacture of ceramic, stone, and clay products         |
| E22 | Manufacture of iron and steel                            |
| E23 | Manufacture of nonferrous metals and products            |
| E24 | Manufacture of fabricated metal products                 |
| E25 | Manufacture of general-purpose machinery                 |
| E26 | Manufacture of production machinery                      |
| E27 | Manufacture of business-oriented machinery               |
| E28 | Electronic parts, devices, and electronic circuits       |
| E29 | Manufacture of electrical machinery, equipment, and supplies |
| E30 | Manufacture of information and communication electronics equipment |
| E31 | Manufacture of transportation equipment                  |
| E32 | Miscellaneous manufacturing industries                   |
| F   | Electricity, gas, heat supply, and water                 |
| G   | Information and communications                           |
| H   | Transport and postal activities                           |
| I   | Wholesale and retail trade                               |
| J   | Finance and insurance                                    |
| K   | Real estate and goods rental and leasing                  |
| L   | Scientific research, professional and technical services |
| M   | Accommodations, eating and drinking services             |
| N   | Living-related and personal services and amusement services |
| O   | Education, learning support                              |
| P   | Medical, health care, and welfare                        |
| Q   | Compound services                                        |
| R   | Services (not elsewhere classified)                      |
| S   | Public service                                           |
| EE  | (Not classified processes in this study)                  |

utilize them and not on the year and country/locations. The technology development of such well-developed technologies has not increased power conversion efficiency, but expanded applicable range of capacity; for example, micro gas turbine could be used for small-scale power generation (e.g., 100 kW). Engines (i.e., GE or DE) have relatively high power conversion efficiencies. Stirling engines have been adopted in small-scale cogeneration. GT has a middle level of power conversion efficiency among the engines and steam turbines. Organic Rankine cycle engines have different properties compared with steam turbines. They have a higher efficiency than steam turbines in the range 200 to 1,000 kW. The required amount of materials for constructing energy plants is shown in Figure S8 in the supporting information on the Web. GT require fewer construction materials than do DEs and GEs. Note that these results are based on available operational records. Because these results are based on past operational results, there is the possibility that a significant improvement in efficiency and material requirements will arise from future innovations.

Scenario Analysis

Figure 7 shows some results of the scenario analysis, representing the life cycle GHG (LC-GHG) emissions (table 1) from the generation of 1 MJ of heat using a cogeneration system (see also Figure S11 in the supporting information on the Web for LC/fossil oil consumption). The results of LC-GHG and fossil oil consumption have mostly the same tendencies: The LC-GHG results mainly originate from the combustion of fossil resources. The LC-GHG value is the summation of the manufacturing, installation, and operational data of a cogeneration system. The subtraction of LC-GHG values from the replacement of public electricity with electricity generated using a distributed technology is also included in the values shown in figure 7. Among the life cycle stages of a cogeneration system, the operation of the system and the subtraction of GHG emissions generated by electricity are the dominant stages. A summation of these absolute values constitutes >98% of the total LC-GHG emissions.

As shown in figure 7, cogeneration systems have a greater performance in countries that have higher GHG emissions in producing electricity. Because engines have a higher power conversion efficiency, they can achieve lower LC-GHG contributions per MJ of thermal power generated. This also results in a high sensitivity to changes in the power mix regarding the effect of cogeneration. As shown in Figure S9 in the supporting information on the Web, the environmental impact from electricity production is reduced significantly by installing low carbon power sources in the IEA Blue Map scenario, which resulted in the temporal change in the decreasing contribution of cogeneration to the decrease of LC-GHG shown in figure 7; in other words, the GHG emission per thermal energy from cogeneration is increasing. For example, water hydroelectric generation is largely installed in China and Latin America, and nuclear electric generation is installed in China, India, the United States, and the OECD Pacific. When these low-carbon
technologies are installed, the advantages of using a cogeneration system decrease. This tendency is increased when using engines rather than turbines. Turbines have a relatively low power conversion efficiency, which leads to a slight decrease in the advantages of a cogeneration system. However, in this regard, technology development and the strategic utilization of cogeneration systems should also be considered when examining the potential of cogeneration systems. The impact relating to a shift in fuels from fossil fuels to renewables, the load following capacity of power sources, and the resiliency of distributed energy sources need to be considered (see also the Discussion section).

**Discussion**

Bibliometric analysis classified the major keywords and concerns for cogeneration, which included not only technology development, but also the requirement for an adjustment of the demand-side conditions. Such a method using machine learning could play a role in supporting continuous discussion because it enables automatic reanalysis based on stored information, as schematically shown in Figure S1 in the supporting information on the Web. In the next section, the topics of distributed energy-source technology are discussed, which is mainly illustrated by Clusters 1, 2, and 3 in figure 2. Statistical analysis can also be automated by establishing appropriate algorithms.
In this article, some energy demand-side aspects were clarified based on the results of bibliometric analysis. The scale factor was confirmed through a statistical analysis of past operational records. The power-to-heat ratio should match the demand-side conditions, which are diversified as shown in figure 4, because any mismatch may cause additional exergy loss and decrease the advantages of cogeneration.

Multigeneration and Symbiosis with Applicable Technology Options

Energy management using IS can increase the advantages of cogeneration not only from a fundamental technology development perspective, but also from an operational and control perspective. It may also support the penetration of cogeneration systems into commercial and industrial sectors where cogeneration systems can potentially be adopted. If public power generation shifts to a large adoption of distributed energy sources, then the power generation sector is also a potential user of cogeneration systems. Even in Denmark, which has the highest CHP ratio in its power grid in figure 5, much of the electricity is supplied by fossil-based single-power generation technologies (Energinet.dk 2014), which can be potentially replaced by CHP technology even though the load following capacity of grid should be taken into account. In Japan, power generation using fossil fuels may involve much heat loss (Koyama et al. 2014). Note that the highest power conversion efficiency may be achieved from a centralized large, single-power generation technology, such as GCC. For supplying electricity only, such technologies may have advantages regarding their conversion efficiency. CHP has advantages in the use of heat, which means that this technology should be located around consuming areas, if no heat transfer or storage technology is available. CCHP can also be an option for installing multigeneration technologies. For indoor farming plant systems (Kozai 2013), for example, electricity, cooling, and heating are definitely the most important requirements. An increase in the efficiency of their supply can lead to an enhancement of productivity from such newly installable technologies.

In the IEA Blue Map scenario, a large amount of thermal power generation remains, even in 2050, which may be necessary, and the viewpoint of the mitigation of frequency fluctuations in the power grid. At the same time, the recovery of heat can work in reducing the consumption of nonrenewable resources for heating. In particular, for biomass power generation mixing increasingly in the power grid in all countries in 2050, CHP systems are significantly effective. This is because biomass resources are distributed thinly and broadly, and collecting them together can lead to savings if distributed power plants are available in a local area where biomass resources can be extracted. Because biomass resources contain much water, which loses generated energy as the evaporative latent heat, a lower power conversion efficiency may be achieved with them than with fossil resources. CHP systems are a key technology for utilizing biomass resources effectively, as has already been demonstrated in sugar mills and sawmills.

Multigeneration of high value-added products (i.e., foods or materials) and biomass for fuel, heat, and power can be a typical mechanism for utilizing biomass resources. Representative examples of high value-added products are items such as sugar, lumber (e.g., Hitoe and Hattori 2011), commodity plastics (e.g., Kikuchi et al. 2013), and industrial solvents (e.g., Nguyen et al. 2011). The raw materials for these industries (i.e., logs, sugarcane, and corn) form residues after producing the main product, and this can be utilized as a biomass fuel for thermal power generation. Thermal power generation can be employed to provide the load to the power grid, and using biomass as a fuel, renewable power sources can become more stable than systems with only photovoltaic and wind turbine power generation.

Fuel cells or gasification have been discussed in the context of the recovery of heat for power generation. In Japan, a market for fuel cells used in houses has been opened (Koyama et al. 2014) and contributes to the reduction of GHG emissions (Kikuchi et al. 2014). The efficiency of fuel cells has been considered for both power generation and heat utilization, which may mean that the utilization of waste heat after the oxidation of hydrogen needs to be included in the mechanism of the fuel cell. The waste heat generated is dependent on the temperature of the fuel cell. Among the several types of fuel cells developed, solid oxide fuel cells (SOFCs) (table 1) have the highest operating temperatures (around 1,000°C). Their waste heat can be utilized in steam production for power generation (Kato et al. 2010). For the use of waste heat as a hot water supply, other types of
fuel cells, such as polymer electrolyte fuel cells (PEFCs) (table 1), can also be utilized in residential sectors in Japan. Note that SOFCs have less energy loss originating in the conversion of fuel to hydrogen than do PEFCs. In the actual use of fuel cells in existing infrastructure, the appropriate type of fuel cell should be selected. Gasification has also been developed and is under consideration for large-scale implementation and the development of micro-GT enables biomass gasification to be considered.

**Challenges for Practical Implementation of Decentralized Technologies**

Although a heat-quantity–based survey was already presented in the previous study (e.g., Chan et al. 2013), the frequencies can represent the potential numbers of cogeneration systems to be newly installed. Though the survey cannot be done perfectly and has a limitation regarding the inclusion of manufacturing processes, the frequency analysis depicted the largest contribution of the low-temperature heat demand. At the time of installation of new cogeneration capacity, actual implementation should be able to take into account the actual conditions of energy demand; especially, the power-to-heat demand has a large influence on the performance of cogeneration system. The technologies have their own such ratio (see also Figure S10 in the supporting information on the Web). The capacity of a system also changes the ratio. The operation ratio of cogeneration systems also has an influence on the conversion efficiency as well as the contribution of initial installation to total environmental impacts. The operation mode (e.g., the mode for maximizing electricity or thermal energy) also has such influence, just as the driving mode of automobile changes the fuel efficiency considerably.

To devise an effective energy management strategy with a cogeneration system, not only should a static analysis based on the scenario parameters of process design be used, but also dynamic analysis that includes aspects of operational design is strongly needed as discussed in the process development frameworks (e.g., Kikuchi and Hirao 2009.). Operation design should be conducted with detailed analysis of current energy demand considering the quantity (J), capacity (watts; W), and quality (°C). Additionally, the socioeconomic aspects of multigeneration technologies should be taken into account for energy management strategy as discussed in Cluster 9 of bibliometric analysis. Especially for renewable resources, their large-scale introduction into society may change the critical paths attributable to GHG emission, as discussed by, for example, Oshita (2012). For example, the collection of biomass resources can lead to the growth of job creation in the primary industries. It may change the structural paths on energy resources. At that time, the social impacts discussed in social LCA (e.g., UNEP 2009) should also be addressed. The scenario analysis in this article can be employed as an analysis of system design of distributed energy sources.
We have reviewed the existing research into energy technology, especially cogeneration systems for CHP, from an analysis of the citation network composed of articles discussing cogeneration technologies. Multigeneration, including electricity, hot or cold heat, or high value-added products, should be considered, especially for process systems utilizing renewable resources. Through the clustering of citation network of cogeneration articles, the approach of this study can be objectively supported. The analysis here can be treated as new information stored, as shown in Figure S1 in the supporting information on the Web. The current situation regarding energy supply/demand on the demand-side sectors in Japan were also reviewed based on available statistical data and an investigation into industrial factories. Many manufacturing processes require low-temperature heating. The possibility exists to replace conventional single-generation technologies, such as boilers or power generators, with multigeneration technologies, such as DEs, GEs, GTs, or fuel cells (see table 1 for full forms of abbreviations). The modeling of past records of cogeneration technologies demonstrates that efficient power generation based on thermal energy conversion plants has a scale dependency, in other words, large-scale plants have an advantage in power generation. A scenario analysis was conducted on the future possibilities of distributed energy sources to clarify the contribution of these technology options, and their penetration scenario was modeled to achieve a total change in fuel consumption. A change in the grid power mix is one of the most sensitive parameters affecting the performance of cogeneration technologies.

Through a trans-sector symbiosis mechanism for sharing energy, distributed energy sources have the potential to reduce fossil fuel consumption significantly in all sectors. A mismatch of the quality of energy, especially heat, or the scale merits of energy technologies can decrease the incentive to implement distributed energy technologies. As a requirement of a regional energy design and management system, distributed energy sources should be considered so that the appropriate
technology options can be adopted for the right task of supplying energy for demand-side sectors.

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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 includes information on the framework of analyses; distributed energy plants attached to production processes; illustrative results of bibliographic analyses; citation networks related to cogeneration, trigeneration, and co-production; product process temperatures; resource consumption in the subdivisions of Japanese industrial and commercial sectors; energy demand/supply based on technologies in Japanese industrial and commercial sectors; the amount of materials required to construct an energy plant; greenhouse gas emissions; and scenario analysis and citation analysis results.