A Comparative Study of the Distributed Co-generation System and the Centralized Grid with Heat Pump System Using "Energy Chain" Concept

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It is necessary to ensure that prospective energy technologies are really energy conservative and contribute to greenhouse abatement over the whole spectrum from producing the energy through transmission, utilization and end use. The "Energy Chain" methodology is proposed as an effective evaluation tool for this purpose. The energy chain concept is defined as energy flow from source to "end use energy benefit" in terms of heating/cooling, hot water, lighting and other benefits of energy through final energy consumption. Two indices are proposed to measure the effectiveness of this process. The first of these is the Energy Chain Joule Index (ECJI) that expresses the extent of energy conservation. The second is the Energy Chain Carbon Index (ECCI) that expresses the extent of greenhouse abatement. For example, residential energy systems for the next decade in Japan are evaluated in terms of the "Energy Chain" concept. Such processes as distributed co-generation are compared with power from the centralized grid and heat pumps to show the relative effectiveness as shown by the two indices listed above. The result of this study shows strict limitations with respect to distributed co-generation systems when compared with central grid energy supply. The available co-generation system must be of high power generation efficiency even when the overall performance is high.

1. Introduction

In recent years, the developed countries proposed international agreement to make concerted efforts for energy conservation and greenhouse abatement. From the stand point of energy policy in the developed countries there have been numerous activities for improving many kinds of efficiencies of engines and other energy conversion equipments by national and local governments, by the industry, by the academia, and by the general public.

Optimization of a part of an energy system is not always best for the overall system. Emphasis is necessary on the importance of evaluating the overall energy demand/supply system from the use of resources not to the final energy consumption, but to "End-use Energy Benefit". In order to try and capture this overall picture, the authors have also introduced a new concept of "Energy Chain" to evaluate the individual energy systems providing energy benefit for effectively minimizing future energy consumption and greenhouse gas release.

In addition to the energy chain concept there is a need for acceptable quantitative criteria for measurement of the effectiveness of a particular energy chain both with respect to energy efficiency and greenhouse abatement. There is also a need for criteria for comparing the relative effectiveness of two possible means of using energy for a defined resulting energy benefit. This would enable decisions to be made on which energy chain path should be taken to minimize energy consumption and maximize greenhouse abatement.

This report first discusses on the structure of the overall energy chain to identify the competitive energy chain or paths in bold relief from the energy resources to resulting energy benefit. It then proposes energy chain indices to evaluate the potential contribution to energy conservation and greenhouse abatement of a specific energy chain. Finally, this report also discusses the quantitative comparison of the distributed co-generation system and the centralized grid power system with heat pumps.

2. Energy Chain of New Concept

2.1. Structure of Energy Chain Energy originally comes from the energy resources; renewable energy resources, fossil fuel mines, uranium mines, and others including the environment. It is converted into secondary energy in the states easy to transport, and consumed by the end-user. At the end-use side, there are many kinds of energy equipment; e.g. fuel combustion equipment, air-conditioners and water heaters working by heat pump and so on to consume energy. The energy is converted into the final end-use energy benefit by these equipments. When we use energy to do something, what we really want is "Energy Benefit". What the energy end-user needs is the energy benefit. The energy benefit may include space lighting, force or power to move something, and comfortableness such as air conditioning and hot water, but neither city gas/oil nor electricity, the provider of this benefit.

Figure 1 shows the basic concept of the energy chain that authors propose. Energy is collected at the resource side (at the left end of the energy chain in the figure), converted into secondary energy, for example city gas, electricity, di-methyl-ether (DME), hydrogen (H_2) and etc. at a certain efficiencies discharging carbon dioxide to the environment (as shown below). The produced secondary energy transmitted through the network and consumed on the demand sides. In the figure, at the exit of conversion block the secondary energy is classified into two kinds of path; electricity and gas / clean fuels.

The secondary energy is consumed by the energy end-users with many kinds of equipments and tools to create energy benefit that is shown at the right hand end of the figure and is located beyond the final consumption of fuel or electricity. Some of the end-user's equipments are competitive to meet the same energy benefit. The end-use energy benefit changes always.

The energy path, or the overall system from the end-use energy benefit to the uppermost part of the stream of the energy flow can be called "the energy chain." There are a number of different energy chain paths between the resource side and the end-use energy benefit side. However, it is also important to overview the "entire energy chain" to understand it. Some of these paths are more efficient than others with respect to the eventual end use energy benefit. Because in many countries in the world the demand of commercial / residential energy use is still increasing, the authors are interested in such an energy use for the benefit.

The energy demanded can be supplied through almost two kinds of path; one is through the electricity driven machinery and/or heat pumps from the power network, and the other is from the distributed co-generation system.

2.2 Proposal of Energy Chain Indices Authors define two indices with a satisfactory means of identifying the energy and greenhouse related characteristics of a specific energy chain. These indices can also be used to compare and evaluate two competing energy systems or technologies to see which is the more appropriate to achieve the required end-use energy benefit and the more greenhouse abatement.

The first of these indices is the Energy Chain Joule Index (ECJI). This is the factor representing the degree of energy conservation.

$$\text{ECJI (-)} = \frac{\text{End-use energy benefit}}{\text{Primary energy consumption for end use}} \tag{1}$$

ECJI is a dimensionless ratio of end-use energy benefit (demand) to primary energy consumed. A larger value indicates an effective energy chain with respect to energy conservation. ECJI can be larger than 1 when a heat pump of high performance is used with high efficiency power

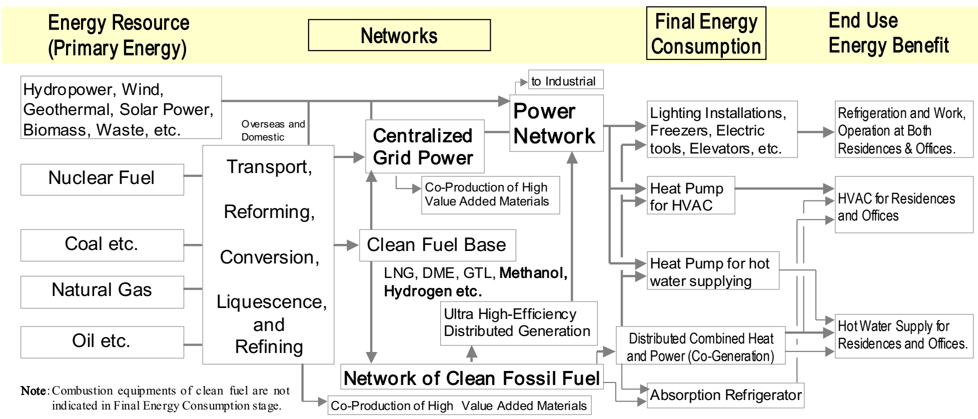


Fig. 1. Overview of entire Energy Chain for commercial / residential end-use.

generation.

The second index is Energy Chain Carbon Index (ECCI). This index is to evaluate the carbon release from the primary energy consumed.

$$\text{ECJI (kJ/kg-C)} = \frac{\text{End-use energy benefit}}{CO_2 \text{ produced from primary energy for end-use}} \quad (2)$$

This is not dimensionless. It should be noted that if the energy resource is renewable or nuclear with no CO_2 released, the value goes to infinity. A high value indicates that the end user benefit is very sparing with production of CO_2 while a low value indicates that the process is relatively poor with respect to greenhouse abatement. ECCI expressed in the reciprocal value of the ratio is also available to compare energy systems and technologies.

3. Energy Chain Evaluation Example –Two Energy Chains for Residential Energy Use

3.1. Basis for Analysis In this section, two Energy Chains will be evaluated in terms of energy conservation and greenhouse abatement, and equivalent energy conservation and greenhouse abatement conditions will be obtained.

The first energy chain consists of the grid power network and a high-efficiency heat pump in Fig. 2(a), indicated by (EC-GH). This system seems to be an ideal co-supplying system. The second energy chain is a co-generation system in Fig. 2(b), indicated by (EC-CG). In recent years, new residential co-generation systems with a power capacity of about 1kW have been commercialized, and these systems are said to be examples of energy conservation and greenhouse abatement.

It is to be noted that EC-CG meets restricted demands only; that is EC-CG can provide electricity and heat energy with a certain ratio depending on the power generating efficiency and heat recovery efficiency. We decide, therefore, to use “rated demand” for energy chain analysis. The rated demand (rated end use energy benefit) comes from following basis; (1) demand data are classified into just two classes, electricity and heat, (2) demand data do not depend on time, and (3) the demand ratio of heat to electricity, ϕ (=heat / electricity), is fixed and equals the ratio of heat recovery efficiency to power generation efficiency of co-generation system ($=\eta_{cgh}/\eta_{cge}$).

3.2. Derivation of Equivalent Conditions. The total electricity consumption of EC-GH is the sum of electricity-demand and electricity-consumption by the heat pump. The primary energy input of EC-GH, F_{GH}, is then the product of the total electricity consumption and the primary energy input per unit of electricity, ($1/\eta_g$), then $F_{GH}=E\ (1+\phi/\xi_{HP})/\eta_g$. CO_2 emission of EC-GH, C_{GH}, is the product of the total electricity consumption and the CO_2 emission factor, U_g, then $C_{GH}=EU_g\ (1+\phi/\xi_{HP})$. Therefore, $ECJI_{GH}$ can be expressed by Eq. (3) and $ECCI_{GH}$ by Eq. (4).

$$ECJI_{GH} = \xi_{HP} \cdot \eta_g (1+\phi)/(\xi_{HP}+\phi) \quad (3)$$

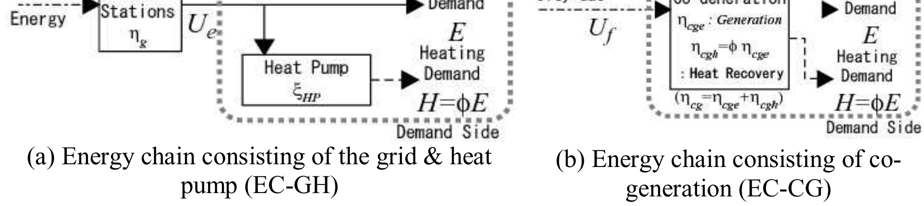
$$ECCI_{GH} = \xi_{HP}(1+\phi)/\{U_g(\xi_{HP}+\phi)\} \quad (4)$$

In EC-CG, the amount of primary energy input can be expressed by $F_{CG}=E/\eta_{cge}$ and CO_2 emission is expressed by $C_{CG}=EU_f/\eta_{cge}$. Therefore, $ECJI_{CG}$ can be expressed by Eq. (5) and $ECCI_{CG}$ by Eq. (6).

$$ECJI_{CG} = \eta_{cge}(1+\phi) \quad (5)$$

$$ECCI_{CG} = \eta_{cge}(1+\phi)/U_f \quad (6)$$

The condition that $ECJI_{CG}$ is higher than $ECJI_{GH}$ can be expressed by Eq. (7). Eq. (8) shows the condition that $ECJI_{CG}$ equals $ECJI_{GH}$. The condition that $ECCI_{CG}$ is higher than $ECCI_{GH}$ can also be expressed by Eq. (9), and the equal CO_2 emission condition can be expressed by Eq. (10).



(a) Energy chain consisting of the grid & heat pump (EC-GH)

(b) Energy chain consisting of co-generation (EC-CG)

Fig. 2. Schematic diagram of simplified EC.

$$\xi_{HP}\cdot\eta_g/(\xi_{HP}+\phi)<\eta_{cge}<1/(1+\phi) \quad (7)$$

$$\eta_{cge}=\xi_{HP}\cdot\eta_g/(\xi_{HP}+\phi) \quad (8)$$

$$\xi_{HP}\cdot U_f/\{U_g(\xi_{HP}+\phi)\}<\eta_{cge}<1/(1+\phi) \quad (9)$$

$$\eta_{cge}=\xi_{HP}\cdot U_f/\{U_g(\xi_{HP}+\phi)\} \quad (10)$$

Equivalent energy conservation conditions can be obtained by making the ECJI of both Energy Chains equal, and can be expressed by Eq. (8). The equivalent greenhouse abatement condition is described by Eq. (10).

3.3. Presentation of Index Information, ECJI and ECCI Maps To evaluate Energy Chains easily, an "ECJI map" and "ECCI map" are presented in Figs. 3 and 4. These maps have an orthogonal coordinate system with demand ratio of heat to electricity (ϕ) on the x-axis and power generating efficiency of co-generation (η_{cge}) on the y-axis. Moreover, ϕ, η_{cge}, and η_{cgh} are connected with a relation-equation, $\eta_{cge}\,\phi = \eta_{cgh}$, because of using the rated demand. Each point on these maps represents a different co-generation system with its own unique efficiencies.

In Fig. 3, a thick-dashed curve and a thick-solid curve divide the map into three areas. The dashed curve represent theoretical maximum of co-generation efficiency, which means total efficiency of co-generation equals 100%. Therefore, in the top-right area of the map (AREA 0), co-generation is impossible because the total efficiency of co-generation systems exceed 100%. The solid curve represents "energy conservation competitive border" which expresses Eq. (8), equivalent energy conservation condition. In the area enclosed by two curves (AREA 1), co-generation system is advantageous to energy conservation as compared with co-supplying system that consists of the grid and heat pump. In the other area (AREA 2), co-generation is disadvantageous to energy conservation. The above explanation is the same about ECCI map except for using "greenhouse abatement competitive border" which expresses Eq. (10), equivalent greenhouse abatement condition.

In Figs.3 and 4, two fine-dashed curves are also drawn, which show total efficiency of co-generation is 80% and 60%.

In Japan, the grid power consists of all power sources including thermal, hydraulic and nuclear power. The values of the CO_2 emission factor, primary energy input per unit electricity and heat pump efficiency are U_g = 0.028 (kg-C/MJ), U_f = 0.014 (kg-C/MJ), and η_g = 35%, ξ_{HP} = 4. Analysis results are plotted in Figs. 3 and 4. In Fig. 3, an energy conservation competitive border with η_g=35% and ξ_{HP} =4, is shown. In Fig. 4, a greenhouse abatement competitive border that has the same conditions as the energy conservation competitive border is shown. When the energy conservation competitive border and the greenhouse abatement competitive border with the same efficiencies are compared, it turns out that the greenhouse abatement area of EC-CG is narrower than its energy conservation area, because the CO_2 emission factor of the centralized grid is low.

3.4. Energy Chain Analysis with Rated Demand

A gas-engine (GE) co-generation system and a polymer electrolyte fuel cell (PEFC) co-generation system are selected as EC-CG examples. In the GE system, η_{cge} = 18% and η_{cgh} = 59%, so E=18 and H=58. In the PEFC system, η_{cge} = 28% and η_{cgh} = 38%, so E=28 and H=38.

Although η_{cg} is as high as 77%, its η_{cge} is as low as 18%, and $ECJI_{CG}$ (GE) is lower than $ECJI_{GH}$. Although η_{cg} is as low as 66%, its η_{cge} is as high as 28%, and $ECJI_{CG}$ (PEFC) is higher than $ECJI_{GH}$.

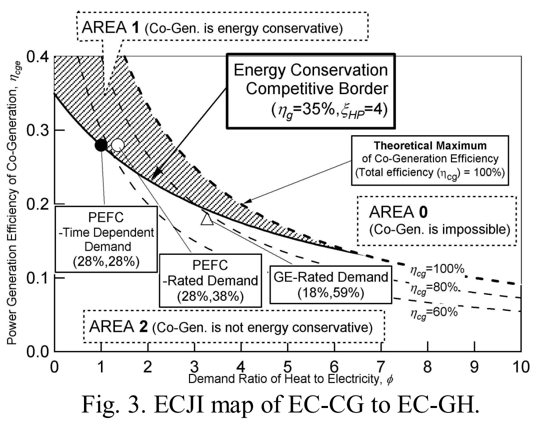


Fig. 3. ECJI map of EC-CG to EC-GH.

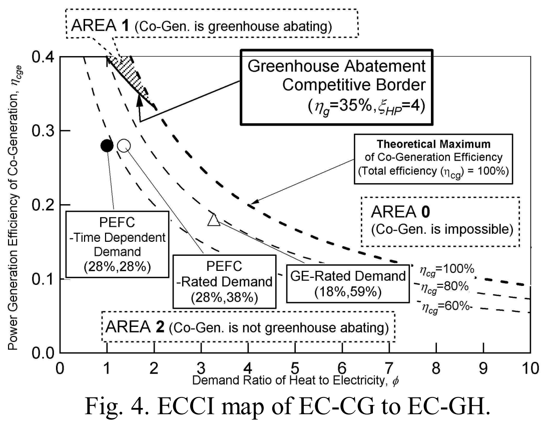


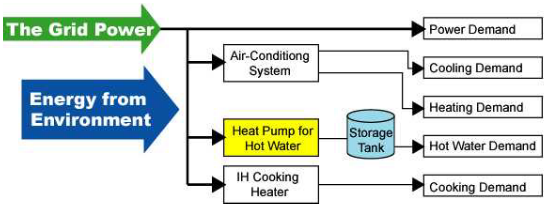
Fig. 4. ECCI map of EC-CG to EC-GH.

3.5. Energy Chain Analysis with Time-Depending Demand Because the end-use energy benefit may vary depending on the season of the year and time of day, energy supply systems must either be installed to deal with the maximum demand or combined with other available energy chains. In other words, the supply system must be appraised by taking into account the availability of energy storage and the use of multiple energy chains.

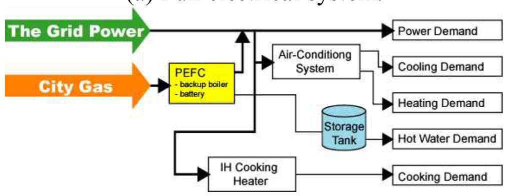
The end use energy benefit data are calculated with the following assumptions; (1) father, mother and two children are living, (2) annual income exceeding 10,000,000 yen, (3) stand-alone house, (4) floor area 150 m^2 and (5) location south of Tokyo. The data are classified into five classes (electricity, cooling, heating, cooking and hot water supply). There are 12 days of data, which are representative in each month, and there are 24 hours' data for each day.

In order to meet this demand, two kinds of "Energy Chain" are considered, as shown in Fig. 5. One is an "full electrical system" in which all kinds of demand are met by electrically powered equipments (electrically driven air-conditioning system, IH cooking heater and heat pump water heater), the other is a "co-generation system" in which electricity and hot water demand are met by co-generation, and cooling and heating demands are met by an electrically driven air conditioning system. Equipment efficiencies are given in Table 1.

Analysis results that use time-depending demand is presented in Fig. 6 (See reference [1] for more detail of simulation). Because the amount of recovery heat cannot expand with mismatching between the demand for electricity and heat on a daily basis, actual heat recovery efficiency falls 10 points from the set-up efficiency and became 28%.



(a) Full electrical system.

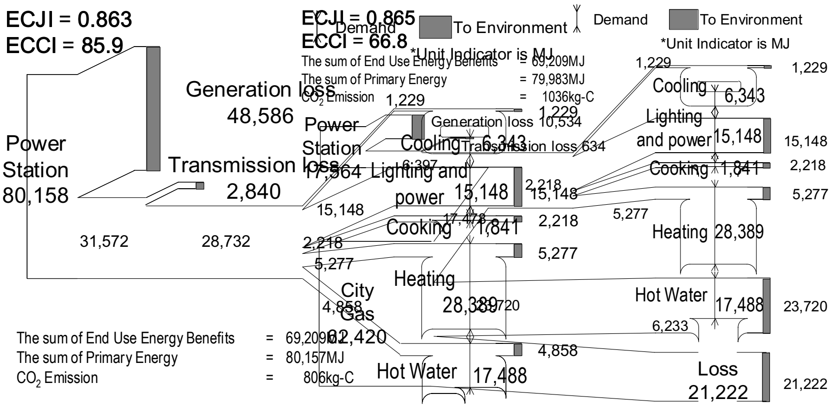


(b) Co-generation system.

Fig. 5. Schematic diagram of Energy Chains for time-depending simulation

Table 1. Equipment efficiency.

	Co-generation	Full electrification
Grid Power (HHV)	Daytime : 35.1%, Nighttime : 37.4% (including transmission & distribution losses)	
Unit Calorific Power	City Gas : 11000kcal/Nm^3	---
CO_2 Emission Factor	City Gas : 0.6325 kg-C/m^3, The Grid : 0.101kg-C/kWh (include all)	
IH Cooling Heater	83%	
Air Cond. Unit	Cooing : 5.16, Heating : 5.38	
PEFC (HHV)	Power : 28%, Heat Recovery 38% (Capacity : 1kW)	---
Heat Pump Water Heater	---	4.0 (Output : .5kW)
Storage Tank	90%	



(a) Full electrical system (b) Co-generation system

Fig. 6. Result of Energy Chain analysis with time-depending energy benefit.

3.6. Interpretation of Results In Figs. 3 and 4, EC-CG(GE) is on the point (x = 59% / 18% =3.28, y = 18%) and is indicated with a triangle. This point is below both the energy conservation competitive border and the greenhouse abatement competitive border, that is EC-CG(GE) is not energy conservative and greenhouse abating. EC-CG (PEFC) with rated demands is on the point (x = 38% / 28% = 1.357, y = 28%), indicated with a circle. This point is above the energy conservation competitive border and below the greenhouse abatement competitive border, that is EC-CG (PEFC) with rated demands is energy conservative, but is not greenhouse abating. Finally, EC-CG (PEFC) with time-depending demands is on the point (x = 28% / 28% = 1.0, y = 28%), indicated with a filled circle. This point is on the energy conservation competitive border (and below the greenhouse abatement competitive border). This reflects the fact that $ECJI_{CG}$ (PEFC) and $ECJI_{GH}$ are almost equal with time-depending demand.

Comparing EC-CG and EC-GH shows that the energy conservation and greenhouse abatement conditions of EC-CG are limited. This implies that the combination of centralized grid and high-efficient heat pump is very effective in energy conservation and greenhouse abatement.

4. Conclusions

The following conclusions can be drawn from this project;

(1) The energy chain concept provides a simple method for evaluating the energy and greenhouse implications of an energy process such that researchers, industry, government and the general public can grasp the important features.

(2) The two Indices ECJI and ECCI enable quantitative indication of the performance of a specific energy related process.

(3) The same two Indices allow direct comparison of the energy conservation and greenhouse abatement values for competing technologies for the same end-use energy benefit.

(4) The examples provided shows strict limitations with respect to distributed co-generation systems when compared with central grid energy supply. The available co-generation system must be of high power generation efficiency even when the overall performance is high.

(5) In order to promote energy conservation and greenhouse abatement for the future, it is essentially important and effective to achieve advanced power generation of higher efficiency whatever centralized system or distributed ones than by the present grid power system and to achieve promote heat pump utilization of higher COP for both air conditioning and hot water supply in commercial/residential energy markets.

Nomenclature

C CO_2 emissions (carbon conversion) (kg-C)

E Electricity Demand

ECJI Energy Chan Joule Index (-),

ECCI Energy Chain Carbon Index (MJ/kg-C).

F primary energy input to energy supply system (MJ),

H Heat Demand

U CO_2 emission factor [CO_2 emission per kWh or MJ] (carbon conversion) (kg-C/kWh) or (kg-C/MJ),

ϕ Demand Ratio of Heat to Electricity (=H / E)

η efficiency (HHV)

ξ COP (coefficient of performance)

[SUBSCRIPTS]

GH Energy Chain consisted of the grid power and heat pump,

CG Energy Chain consisted of combined heat and power,

g the grid power (demand-end),

HP heat pump,

cg total efficiency of co-generation system,

cge power generation efficiency of co-generation system,

cgh heat recovery efficiency of co-generation system.

[CONSTANT]

U_g = 0.37(kg-CO_2/kWh) x 12 / 44 / 3.6

U_f = 51.3(g- CO_2/MJ) x 10^{-3} x 12 / 44

References and Notes

[1] K.Hashimoto, T.Takahashi and M.Saikawa, CRIEPI Report, W03008 (2004) (in Japanese)

[2] T.Hamamatsu, M.Saikawa and K.Hashimoto, Proceedings 19th World Energy Congress, Sydney, (2004) (scheduled)