Chapter 6
Integrated Plan and Evaluation of Distributed Energy System by Area Energy Network in Smart Community Toward Low Carbon Society

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6.1 Distributed Energy with Area Energy Network

### 6.1.1 The Trend of Distributed Energy and Area Energy Network

Distributed energy systems (DES) have been drawing increasing attention as a substitute for grid in the low carbon society development [1, 2]. Compared with the traditional centralized energy supply system, the distributed energy generations are easy for renewable energy use and can avoid the loss in energy delivery as well. As the integration of distributed energy generation become major concerns, one problem occurred that the conventional energy supply model, the unidirectional top-down grid could hardly be multipurpose to it [3]. It can only support the energy flow from the energy station to static users. A much smarter energy supply system will be desirable to support multidirectional energy flows that can dynamically switch between the user and local energy providers. It needs for more observable, accessible, and controllable network infrastructures. The future energy system, termed as area energy system with smart city technologies, is the emerging system.

Area energy network refers to the idea of mutually accommodating electricity and heat among multiple buildings. As Fig. 6.1 displayed, in conventional system, buildings use electricity and heat individually. However, in an energy system based on area energy network, electricity and heat are distributed among multiple buildings to level out usage patterns of electric energy and thermal energy.

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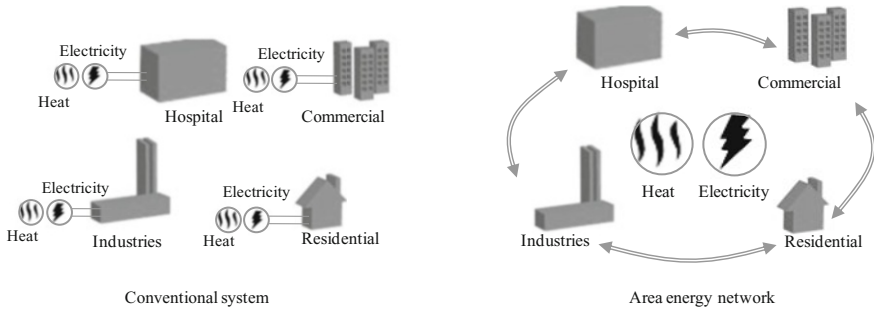
Fig. 6.1 The conventional system and area energy network

6.1.2   General Structure of Area Energy Network

The area energy network within microgrid and distributed generation paradigm should be recognized as the future power paradigm. The model discussed in this chapter is not an isolated system but connected with the conventional system. The system can both import and export surplus electricity at times of low local demand. Area energy network is a network of energy chains, starting from the primary energy supply and ending in the end-user sectors. The main parts of area energy network are primary energy supply sector, energy transformation sector, energy distribution sector, and end-user sector.

Primary Energy Supply Sector
Primary energy supply sector includes the nonrenewable energy (fossil fuel, etc.), renewable energy (solar, biomass, etc.), and untapped energy (industrial by-pass, water energy, etc.).

Energy Transformation Sector
The small-scale distributed technologies will be dominated in the area energy network model with distributed energy generation. The energy transformation sectors as CHP plant make use of the energy from primary energy supply sector and transfer them to the energy in the local network, the energy distribution sector in area energy network.

Energy Distribution Sector
The energy distribution sector is an essential part in the area energy network. It connected the distributed energy generations to form a network with the electricity and heat sharing. The optimization of the distribution sector with the intelligent control can level out the load fluctuation and cut the capital investment, rewarding both in environmental aspect and economic aspect.

End-User Sector

The integrated energy system can supply customers with different kinds of end-use services. In area energy network, the end users usually formed with more than one building. Load profiles represent the basis for generation and distribution system sizing and economic dispatch optimization [4]. Design and plan in the end-user sector is the base for the area energy network.

6.1.3 Classification of Area Energy Network with Heat

Various research about the area energy network is mostly focused on electricity supply chain, among which the heat supply system can hardly be mentioned. This chapter focuses more on the area energy network from the aspect of heat, as heat is also an important aspect for improving the efficiency of area energy network.

From the viewpoint of heat utilization, the area energy network in Japan is classified into three types, according to the scale: the district heating, centralized plant, and the interchanging energy system.

1. **District Heating (Cooling)**

District energy systems (DES), displayed in Fig. 6.2, centralize the production of heating or cooling for a neighborhood or community. It is a large energy plant, supplying energy to a board district. The supply regulations are based on the heat supply business law. The energy is supplied by heat supply companies that are set by the law, and supply obligation is based on the law, defining the conditions by the supply rules.
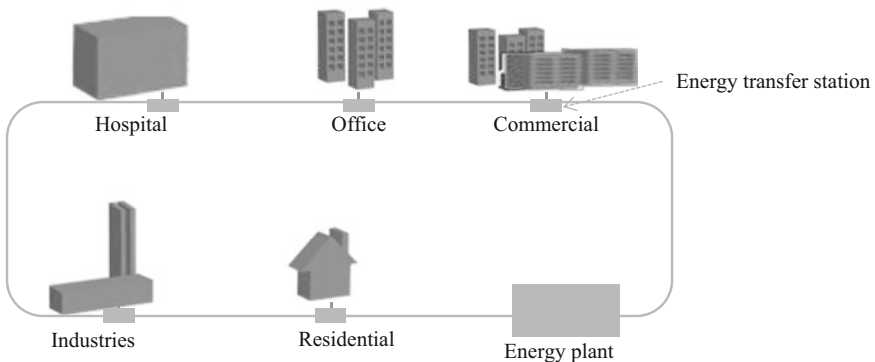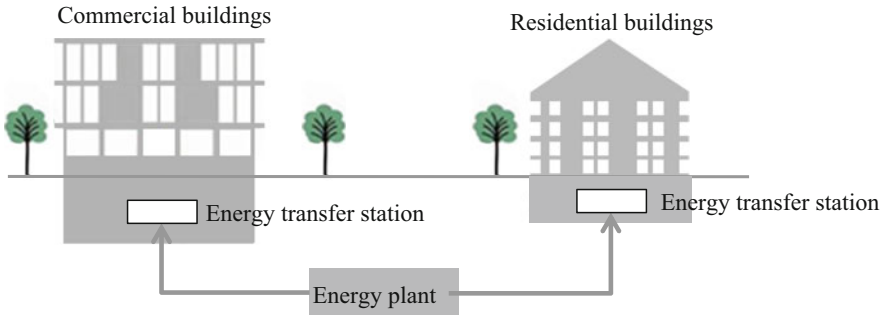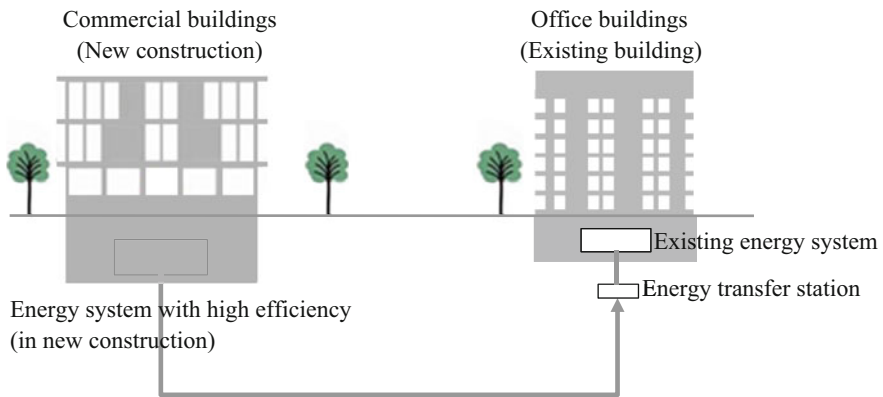

Fig. 6.2 The concept of district heating (cooling) system

Commercial buildings

Residential buildings

Energy transfer station

Energy transfer station

Energy plant

Fig. 6.3 The concept of centralized plant

Commercial buildings
(New construction)

Office buildings
(Existing building)

Existing energy system

Energy transfer station

Energy system with high efficiency
(in new construction)

Fig. 6.4 Interchanging energy system between buildings

2. **Centralized Plant**

Centralized plant, displayed in Fig. 6.3, is almost same with district heating and cooling. It uses centralized heat generation as heat supply system for the customers in the same site. Compared with district heating, centralized plant is in small scale and excluded from the heat supply law. This type is usually called regional heat and cooling, widely used in the residential area, universities, hospitals, and commercial areas.

3. **Interchanging Energy System Between Buildings**

Compared with the other two types before, the interchanging energy system between buildings (displayed in Fig. 6.4) is the area energy network in small scale, with the energy interchanging between buildings. In this kind of project, the nearby buildings are connected with pipes and share the heat. The characteristic of this type is that the buildings in this area network have their own heat generation system as the base heat supply. In other words, the buildings in this type can also
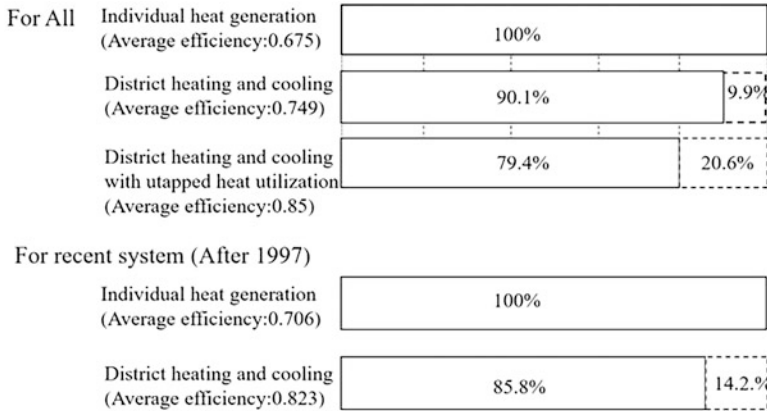
Fig. 6.5 The energy saving effect of area energy network

work individually. However, the efficiency of the heat supply system in the existing buildings can be improved by highly efficient equipment introduction in the new constructions and the energy interchanging management.

6.1.4 Energy Conservation Effect of Area Energy Network

The area energy network aggregates the energy load in the region. In that case, it can adopt more efficient energy generation plant and can manage the system more efficiently to support part load by appropriate equipment division. The optimization of the system construction and controlling can improve the energy saving effect.

The survey [5] in the year 2008, displayed in Fig. 6.5, suggested that the district heat supply system can save 9.9% primary energy compared with the individually heat supply system. Recent systems built after the year 1997 have higher energy efficiency and can save 14.2% primary energy. Further, the distributed heat energy system can utilize the untapped heat resource and realize the 20.6% primary energy conservation.

6.1.5 Planning and Design of Area Energy Network Procedure for Its Introduction

Procedures for the introduction of area energy network are different according to its type, district characteristic, and system form. Usually, the procedure is from the basic concept and the plan of the business, the system design, construction, operation and maintenance, evaluation, and system renovation.
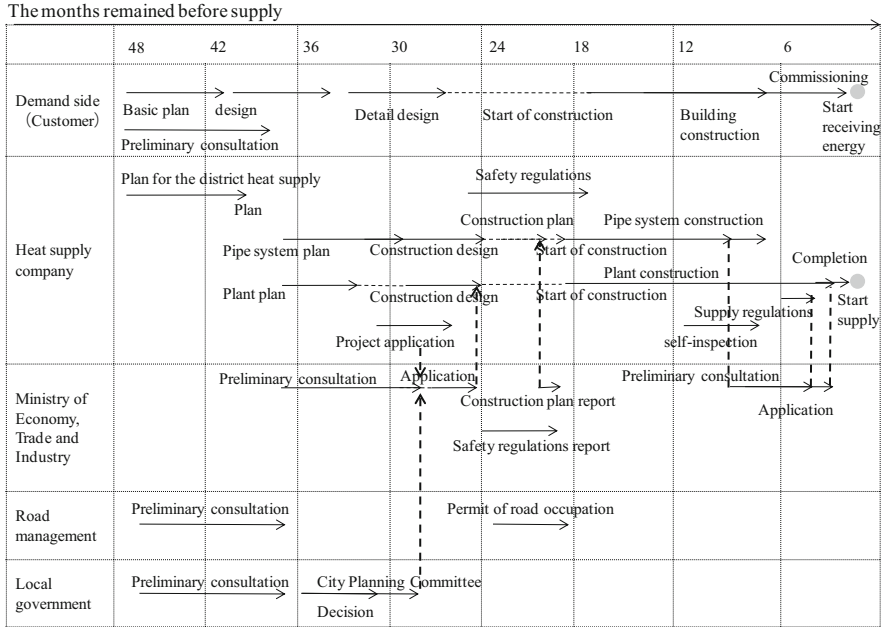
The months remained before supply

	48	42	36	30	24	18	12	6
Demand side (Customer)	Basic plan Preliminary consultation	design		Detail design	Start of construction		Building construction	Commissioning Start receiving energy
Heat supply company	Plan for the district heat supply Plan Pipe system plan Plant plan		Construction design Construction design Project application		Safety regulations Construction plan Start of construction Start of construction	Pipe system construction Plant construction Supply regulations self-inspection		Completion Start supply
Ministry of Economy, Trade and Industry		Preliminary consultation		Application	Construction plan report Safety regulations report		Preliminary consultation	Application
Road management	Preliminary consultation				Permit of road occupation			
Local government	Preliminary consultation		City Planning Committee Decision					

Fig. 6.6 Time schedule for area energy network construction

The area energy network is proposed firstly based on the city development, as the construction or renewal of the urban blocks. Then the developers will analyze the surrounding heat resource and the situation of the heat supply, deciding the type of the project. Figure 6.6 displayed the flow and time schedule for area energy network construction.

The area energy network needs detailed planning during every stage for the survey on the untapped energy use, energy demand side prediction, and plant system setting. Further, it needs more information about the characteristic of the district and the urban plan information to make the project more practicable. Figure 6.7 displayed the considerations in the area energy network planning decisions.

6.2 A Model for Area Energy Network by Offline Heat Transport System and Distributed Energy Systems

Based on the normal area energy network with hit utilization, the heat supply should also convey the concept of distributed energy generation (DEG), demand energy storage (DES), and demand side response (DSR), under the concept of smart city. It can make use of onsite exhaust heat, such as recovery heat of CHP plant and nearby factory exhaust heat (FEH) [6]. It should be a dynamic controllable as well, which can smooth out the heat fluctuation.

Fig. 6.7 Considerations in the area energy network planning decisions

In this part, we develop an area energy network by offline heat transport system and distributed energy systems, with the concept of DEG, DES, and DSR.

6.2.1   The Demand-Response Network Model

The demand-response network (DRN) model for smart community is a treelike hierarchical model that comprises the community energy management system (CEMS), energy station (ES), and building energy management system (BEMS).

Figure 6.8 demonstrated the hierarchical model. The end users (managed by BEMS) reside at the bottom of the hierarchy. They will be prioritized and organized into groups. Every group is managed by one ES. The ES is at the lowest rank unit for the energy strategy decision that controls the introduction of DEG, DES, and DSR. The ES collects information of the energy generation and consumption in the group and sends signals to the CEMS. The CEMS connected with each other and formed city energy network, which is organized in a topological structure. ES is assumed to
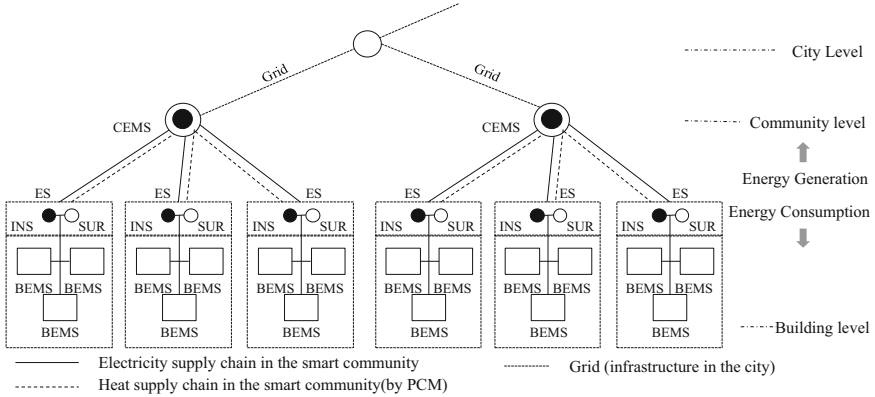
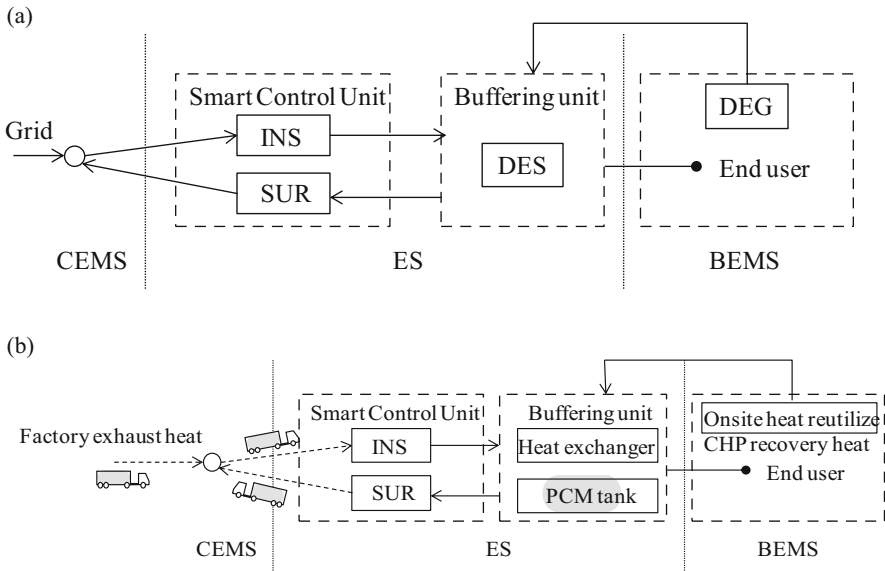Fig. 6.8 The treelike hierarchy of DRS

Fig. 6.9 DRN system energy supply chain (a) Electricity supply chain (b) Heat supply chain

have two modes, the energy surplus mode (SUR) and the energy insufficient mode (INS). The ES can dynamically switch its mode depending on the energy generation and consumption in the group. The mode signal will send to CEMS who collects and distributes the energy.

The proposed DRN system in this research is different from the smart grid that it not only has electricity supply chain but also has heat supply chain. Figure 6.9a illustrated the electricity supply chain. The DES in DRN system only acts as a backup and the buffer unit. The energy produced by DEG is supplied to the end users from the buffer unit. When the energy generated by DEG is more than the energy
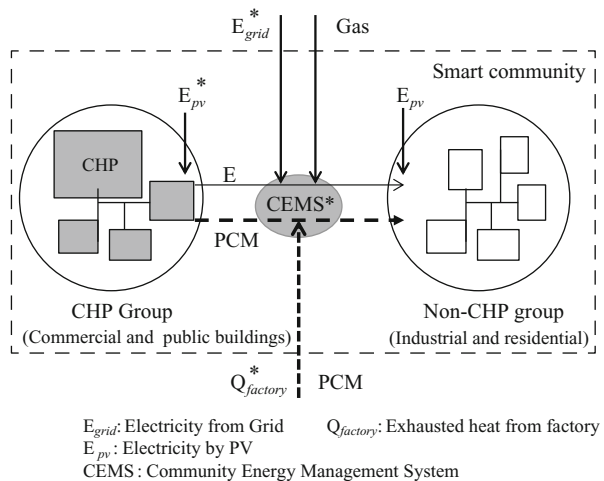
consumption in the group, the ES will be in SUR mode and become an energy supplier to other ES. Oppositely, the ES will be in INS mode when the energy generated by DEG is less than the energy consumption and becomes an energy consumer. Figure 6.9b illustrates the heat supply chain. Similar with the electricity supply chain, it has a buffering unit that comprises the PCM tank and the heat exchanger. Under the INS mode, the CEMS will transport heat to the ES by trucks with PCM tank. Under the SUR mode, the tank in the buffer unit will collect the surplus heat and be transported to other ES when it received the order from the CEMS. The mode signals in the heat supply and that in the electricity supply are self-governed.

6.2.2 District Energy Using Concept and Operation Hypothesis

As the DRN system illustrated before, the building in the community will be divided into groups. Every group is managed by ES, the basic unit to make energy strategies. Figure 6.10 describes the district energy using concept.

1. Introduction of the renewable energy: all the buildings will be introduced with PV system. The electricity generated by PV system will be preferentially used by the building themselves and the remaining electricity will be sent back to the grid.
2. Introduction of the CHP system: the CEMS will characterize buildings by their demand types. The buildings have both high electricity consumption and heat consumption (such as commercial buildings and public buildings) which will be introduced with the CHP system, named as CHP group. The capacity of the CHP system is set as electricity peak load of the group. The buildings without CHP

Fig. 6.10 District energy using concept

E_{grid}: Electricity from Grid $Q_{factory}$: Exhausted heat from factory
E_{pv}: Electricity by PV
CEMS: Community Energy Management System

system is considered as non-CHP (NCHP) group. The electricity produced by CHP plant will satisfy themselves first and then send the remaining electricity to NCHP system. The CHP group will generate all their own demand beside PV. Therefore, as the DRN described before, the electricity of these groups is only in SUR mode. The NCHP group will be in INS mode if PV cannot afford their electricity consumption.

The CEMS will manage the model signal and control and dispatch the electricity. It will preferentially use the DEG, thus maximum output of CHP plant. The electricity produced by PV can sell back to grid, but the electricity produced by CHP plant cannot. In that case, when the electricity generated by the CHP is more than the district electricity demand, the CEMS will restrict the CHP output. It will preferentially choose the CHP plant with higher efficiency and lower down the CHP plant with low efficiency. If the efficiencies of the CHP plants are the same, CEMS will cut down the CHP plants in same rate.

3. Reutilization of the onsite exhaust heat and the FEH: the recovery heat of the CHP system will be preferentially used by the group first. However, if the recovery heat is more than the heat demand, the heat supply mode of the ES will turn to SUR. This part of heat surplus will be collected by CEMS.

Further, the CEMS will select out the FEH resource based on the characteristic of the PCM system, which collects the FEH and utilizes it in the community.

The onsite CHP exhaust heat and the FEH stored in the PCM system will be preferentially used. The CEMS will distribute the heat according to the SUR signal from the ES. It will be sent to the ES which has higher amount of heat insufficiency.

Fig. 6.11 The simulation flow
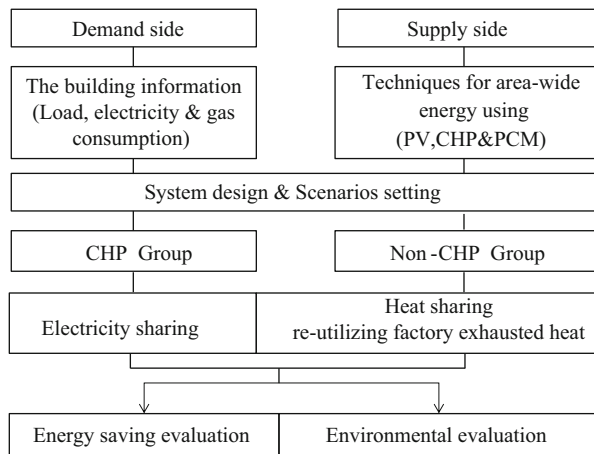
6.3 Energy Balance Management and Simulation Modeling

6.3.1 Simulation Flow

The energy balance management and the simulation flow are conducted as in Fig. 6.11. The simulation of the DRN system is also a bottom-up model. Firstly, based on the district zoning, the research will estimate the building energy consumption and describe profiles by groups. As the treelike hierarchy described in the second part, buildings in one group will be managed by one ES. Secondly, the CEMS will characterize the groups by its energy consumption character and introduce proper DEG in every ES: some are with CHP system, but some are not. The simulation separated them into CHP group and the NCHP group. Thirdly, the research executed the simulation. During the simulation, ES will dynamically switch between the INS mode and the SUR mode by estimating the energy consumption and the generation. Finally, the research will calculate the primary energy consumption and evaluate the environmental effect of every technology as well as the whole community.

6.3.2 Estimation of District Energy Consumption

The energy consumption of the whole community $\left(E_{demand}^{community} \right)$ is calculated as follows (6.1):

$$E_{demand}^{community} = E^1 + E^2 \ldots\ldots + E^n = \sum_n \sum_m \sum_d \sum_i \left(ELEC_{mdh}^n + HEAT_{mdh}^n \right) \quad (6.1)$$

$ELEC_{mdh}^n$ is hourly electricity load, calculated as

$$ELEC_{mdh}^n = \sum_k e_{mdh}^n \times s_k \quad (6.2)$$

$HEAT_{mdh}^n$ is hourly heat load, calculated as (6.3)

$$HEAT_{mdh}^n = \sum_k h_{mdh}^n \times s_k \quad (6.3)$$

n is the group number.
m is month; d is date; h is hour.
E1...En is the energy consumption of every group.
e_{mdh}^n and h_{mdh}^h are the energy consumption unit in Kyushu area, Japan [7].
k is the building function.
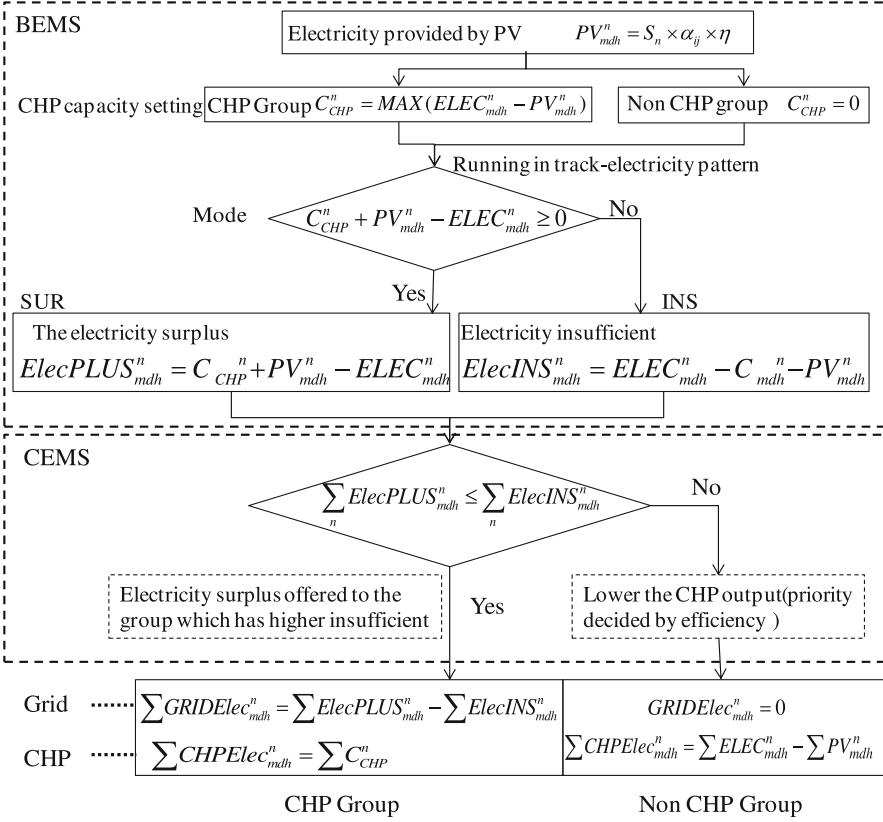S_k is the building area for one function (k).

Fig. 6.12 The electricity balanced model

6.3.3   The Electricity Balanced Management

Figure 6.12 illustrates the simulation model for the electricity balance.

The buildings will preferentially use the electricity produced by PV.

The electricity produced by PV system in one group (PV_{mdh}^n) is calculated as follows (6.4):

$$PV_{mdh}^n = S_n \times \alpha_{mdh} \times \eta \tag{6.4}$$

S_n is the area for PV penal in a group (n).
α_{mdh} is the hourly sun radiation rate [8].
η is the efficiency of the PV penal [8].

The CHP capacity $\left(C_{CHP}^n\right)$ is decided as (6.5).

$$C_{CHP}^n = \begin{cases} \text{MAX}\left(ELEC_{mdh}^n - PV_{mdh}^n\right) & (CHPgroup) \\ 0 & (NCHPgroup) \end{cases} \tag{6.5}$$

The ES will decide the mode by the prediction of electricity load profile of the CHP system, PV system, and electricity demand.

When $C_{CHP}^n + PV_{mdh}^n - E_{mdh}^n \geq 0$, the group is in SUR mode. The expected surplus electricity $\left(ElecPLUS_{mdh}^n\right)$ is calculated as follows (6.6):

$$ElecPLUS_{mdh}^n = C_{mdh}^n + PV_{mdh}^n - E_{mdh}^n \tag{6.6}$$

On the contrary, when the group is in INS model, the expected electricity insufficiency $\left(ElecINS_{mdh}^n\right)$ is calculated as follows (6.7):

$$ElecINS_{mdh}^n = E_{mdh}^n - PV_{mdh}^n - C_{mdh}^n \tag{6.7}$$

If $\sum_n ElecPLUS_{mdh}^n \leq \sum_n ElecINS_{mdh}^n$, CEMS would lower down the total CHP output (prior use of the equipment with higher efficiency). Under this situation, there was no electricity supplement from the grid. The electricity generated by CHP plant $\left(CHPElec_{mdh}^n\right)$ is calculated as follows (6.8):

$$\sum CHPElec_{mdh}^n = \sum ELEC_{mdh}^n - \sum PV_{mdh}^n \tag{6.8}$$

If $\sum_n ElecPLUS_{mdh}^n \leq \sum_n ElecINS_{mdh}^n$, the surplus electricity from CHP group will be offered to the NCHP group. Under this situation, the electricity from the grid $\left(GRIDElec_{mdh}^n\right)$ is calculated as follows (6.9):

$$\sum GRIDElec_{mdh}^n = \sum ElecPLUS_{mdh}^n - \sum ElecINS_{mdh}^n \tag{6.9}$$

Electricity offered by CHP is calculated as follows (6.10):

$$\sum CHPElec_{mdh}^n = \sum C_{CHP}^n \tag{6.10}$$

6.4 The Design and Modeling for the PCM System

### 6.4.1 The Offline Heat Transportation System with PCM

The offline heat transport system, suggested in Fig. 6.13, is the rejected heat transport system without pipeline that can utilize the rejected heat at less than 200 °C. It is a track with a PCM container that can collect storage exhausted thermal energy from the factories and store and then transport to the heat demand area.

The system is firstly developed by the aviators and introduced in Japan from the year 2003 and then became widely used these years. Compared with the traditional pipe system, the offline system can collect heat from all the factories in possible distance rather than one. Furthermore, it can avoid large initiate cost of pipes.

When the heat is used for heating or cooling, the system has three times heat capacity than water; thus, this system can offer a reliable heat supply. In the container, the oil can make a good contact with the PCM material that the heat can transit fast and efficiently to PCM. When the surface enlarged, the speed becomes much faster. The maximum can reach to 0.6 MW [9].

The system firstly collected heat from the supply side, which is then stored and then transported to the demand side. Even heat demanding and discharging of the demand side always fluctuate; the PCM container has a buffer tank which can promise stable supply. There are two energy supply patterns as in Fig. 6.14.

Fig. 6.13 The offline heat transport system
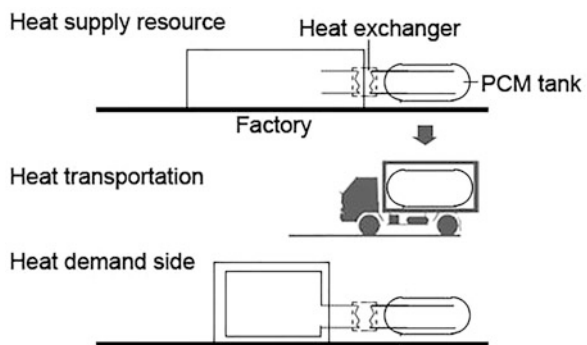
Fig. 6.14 The energy supply pattern of demand side
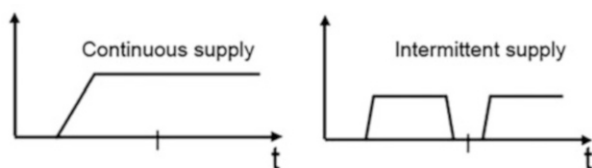
6.4.2   PCM for Collecting the FEH

According to the system parameter, economically the system can utilize heat within 135 km and 20 km round trip [10]. The CEMS will economically select out the possible utilized resource and make a plan for the PCM system. The collecting schedule of the PCM trucks should match with the factory working hour. It will become more complicated as the factory heat resource increases. Considering the various factors for making the plan, the research assumed that the FEH collected would be transported to the demand side and used in the following day.

The number of the tanks for collecting FEH used in 1 day (x) is decided by the capacity ([9]). It should satisfy the following (6.11):

$$Q_{pcm} \cdot x \geq \sum Q_{fac} \qquad x \in (1, p) \qquad (6.11)$$

Q_{pcm} is the capacity for the PCM tank.
Q_{fac} is the daily factory exhaust of the selected resources.

The exhaust heat that can be used in the demand side is limited by the energy lost during the heat storage, transport, and exchange. CEMS will estimate it can select out the proper resource. The amount of heat ($HEAT_{recFAC}$) that can be used in the demand side is as follows (6.12):

$$HEAT_{recFAC} = \mu \cdot Q_{fac} \qquad (6.12)$$

μ is the overall efficiency of the PCM system, set as 0.91 according to the existing research [8] (Table 6.1).

6.4.2.1   PCM for the Heat Delivery Between the Groups

ES will use the estimated consumption pattern for the consistent prediction and send the mode signal to CEMS.

Table 6.1 The type and parameters of the PCM tank

Type	Melting Point/ °C	Heat temperature/°C	Tank capacity/ MWh	Usage Hot Water	Heating	Cooling
Type1	58	85(70)	0.8~1.1	○	○	—
Type2	78	100(90)	—※	○	○	—
Type3	116	150(130)	—※	○	○	○
Type4	118	150(130)	1.1~1.4	○	○	○

※Type2 and Type3 are used outside Japanese   ○ The function it has   — The function it doesn't has

For every group, CHP recovery heat $\left(CHPREC_{mdh}^n\right)$ is as follows (6.13):

$$CHPREC_{mdh}^n = \begin{cases} \dfrac{\eta_h}{\eta_e} ElecCHP_{mdh}^n & (CHPgroup) \\ 0 & (NCHPgroup) \end{cases} \tag{6.13}$$

η_e is the electricity generating efficiency of CHP plant.
η_h is the heat recovery efficiency of CHP plant.

If $CHPREC_{mdh}^n - HEAT_{mdh}^n \geq 0$, the ES is in SUR mode and the expected value of heat surplus $\left(Heat_0SUR_{mdh}^n\right)$ is as follows (6.14):

$$Heat_0SUR_{mdh}^n = CHPREC_{mdh}^n - HEAT_{mdh}^n \tag{6.14}$$

If $CHPREC_{mdh}^n - HEAT_{mdh}^n < 0$, the ES is in INS mode and the expected value of heat shortage $\left(Heat_0INS_{mdh}^n\right)$ is as follows (6.15):

$$Heat_0INS_{mdh}^n = HEAT_{mdh}^n - CHPREC_{mdh}^n \tag{6.15}$$

Every day, the PCM system will carry the FEH and input into the community from the first peak time in the morning, set as h_0 . During the day, the system will preferentially use the heat stored in the PCM and release it before the next day. Therefore, every day at the time h_0 , the heat amount stored in the PCM system is reset.

The amount of stored heat energy in the PCM that can be supplied to the ES in SUR mode at h time in one group $\left(PCMREC_{mdh}^n\right)$ is as follows (6.16):

$$\sum^n PCMREC_{mdh}^n = \begin{cases} \sum^n PCMREC_{md(h-1)}^n + \sum^n Heat_0SUR_{mdh}^n - \sum^n Heat_0INS_{mdh}^n & (h \neq h_0) \\ HEAT_{recFAC} & (h = h_0) \end{cases} \tag{6.16}$$

The total amount of PCM truck (p) should satisfy condition (6.17)

$$MAX\left(\sum^n PCMREC_{mdh}^n\right) \leq Q_{pcm} \cdot p \tag{6.17}$$

$MAX(\cdot)$ is a function to determine the maximum value of the stored heat in PCM system by the expected value.
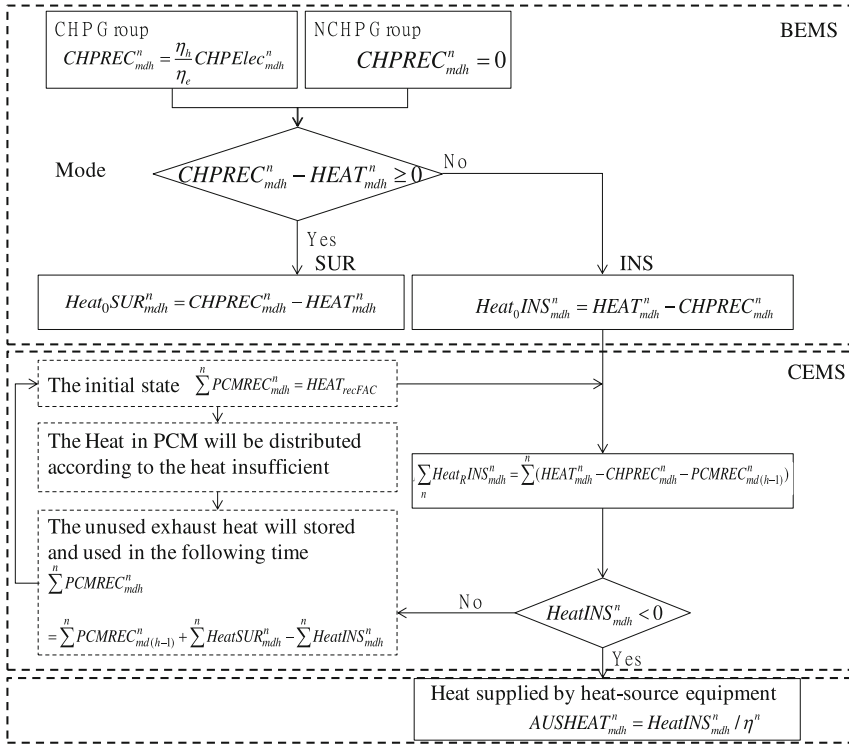
Fig. 6.15 Heat supply calculation flow

6.4.3 The Heat Balanced Management

Figure 6.15 illustrates the heat balanced management. The collected heat in the PCM system including the recovery heat of CHP system and FEH is used for heating, cooling, and hot water in the community. It is also managed by CEMS following total quantity priority that is supplied to the group, which had larger amount of heat shortage, $\mathrm{MAX}\left(Heat_0INS_{mdh}^n\right)$..

With the use of the waste heat collected by the PCM system, the heat shortage $\left(Heat_RINS_{mdh}^n\right)$ is as follows (6.18):

$$\sum_n Heat_RINS_{mdh}^n = \sum_{n}^{n} \left(HEAT_{mdh}^n - CHPREC_{mdh}^n - PCMREC_{md\,(h-1)}^n\right) \quad (6.18)$$

When $Heat_RINS_{mdh}^n \leq 0$, the heat demand can be satisfied with the onsite exhaust heat reutilization that the heat-source equipment $\left(AUSHEAT_{mdh}^n\right)$ is not required (6.19):

$$AUSHEAT^n_{mdh} = 0 \tag{6.19}$$

When $Heat_R INS^n_{mdh} > 0$, the heat-source equipment is used as supplement. The heat offered by the heat-source equipment is as follows (6.20):

$$AUSHEAT^n_{mdh} = Heat_R INS^n_{mdh} / \eta^n \tag{6.20}$$

η^n is the efficiency of heat-source equipment.

6.4.4　Assessment Index Setting

1. Energy saving ratio.

ESR is energy saving ratio, defined as follows (6.21):

$$\mathrm{ESR} = \frac{Q^{Conv}_{input} - Q^{CHP}_{input}}{Q^{Conv}_{input}} \tag{6.21}$$

For CHP system, the primary energy input is as follows (6.22):

$$Q^{CHP}_{input} = E^{CHP}_{Utility} \times \varepsilon_{Grid} + \left(V^{CHP} + V^{Boiler}\right) \times \varepsilon_{gas} \tag{6.22}$$

$E^{CHP}_{Utility}$ is the electricity input in CHP system; V^{CHP}, V^{Boiler} is the gas input to the CHP plant and boiler.

For conventional system, the primary energy input is as follows (6.23):

$$Q^{Conv}_{input} = E^{Conv}_{Utility} \times \varepsilon_{Grid} + V^{Conv} \times \varepsilon_{gas} \tag{6.23}$$

$E^{Conv}_{Utility}$ is the electricity input in conventional system.
V^{Conv} is the gas input to conventional system for hot water.
ε_{Grid} is primary energy consumption unit of grid in Japan (11.4 MJ/kWh)).
ε_{gas} is primary energy consumption unit of city gas in Japan (45 MJ).

2. CO_2 reduction ratio.

$\eta_{\Delta CO_2}$ is CO_2 reduction ratio, defined as follows (6.24):

$$\eta_{\Delta CO_2} = \frac{EX^{Conv}_{CO_2} - EX^{CHP}_{CO_2}}{EX^{Conv}_{CO_2}} \tag{6.24}$$

$EX^{CHP}_{CO_2}$ is CO_2 emission for CHP system, calculated as follows (6.25):

$$EX_{CO_2}^{CHP} = ex_{CO_2}^{gas} \times \left(V^{CHP} + V^{Boiler}\right) \times \varepsilon_{gas} + ex_{CO_2}^{Pow} \times E_{Utility}^{CHP} \times \varepsilon_{Grid} \qquad (6.25)$$

$EX_{CO_2}^{Conv}$ is CO_2 emission for conventional system, calculated as follows (6.26):

$$EX_{CO_2}^{Conv} = ex_{CO_2}^{gas} \times V^{Conv} \times \varepsilon_{gas} + ex_{CO_2}^{Pow} \times E_{Utility}^{Conv} \times \varepsilon_{Grid} \qquad (6.26)$$

$ex_{CO_2}^{gas}$ is the CO_2 emission unit for gas in Japan (13.8 g-C/MJ).
$ex_{CO_2}^{Grid}$ is the CO_2 emission unit for grid in Japan (153 g-C/kwh).

A numerical study of this model is presented in a smart community in Kitakyushu, Japan. In order to provide a smart community model with low carbon concept, the latest DEG technologies, such as gas engine, fuel cell, hydrogen fuel cell, PV, PCM system, untapped FEH, etc., are considered in the model. By analysis on various cases, the study will suggest the environmental effect of every technology as well as the overall potential of the smart community in Japan.

6.5 Case Study

6.5.1 Energy Load

Kitakyushu lied in the northern part of Kyushu, the westernmost of the four main islands in the Japanese archipelago. It used to be one of Japan's four leading industrial regions and contributed greatly to the rapid economic growth of Japan [11].

The smart community creation project is newly launched in Yahata Higashi district, where it used to be the factory district of the steel company. The government invested 16.3 billion yen over the 5-year period from 2010 to 2014. It has already cut 30% of the CO_2 emission compared with the other place in the city. However, the target for the smart community was to cut 50% of the existing emission, but still 20% need to be cut.

The urban structure has been changed in the past few years under the concept of "Environmentally Growing Town" and "Creation of a Shared Community." Commerce, entertainment, museum, and residential buildings were introduced into this area, which made a "compact district" with mixed function.

Detailed knowledge about energy end-use loads is important for the energy system design and optimization. In this study, the hourly load demand for electricity, cooling, heating, and hot water has been calculated according to the energy consumption unit (the system in Japan that displays energy consumption intensities) of various buildings in Kyushu, Japan [7]. As the method described before, the whole community is divided into four groups. Figure 6.16 displays the image of community and district zoning. The building information, yearly energy consumption, and peak load of the district are shown in Table 6.2.
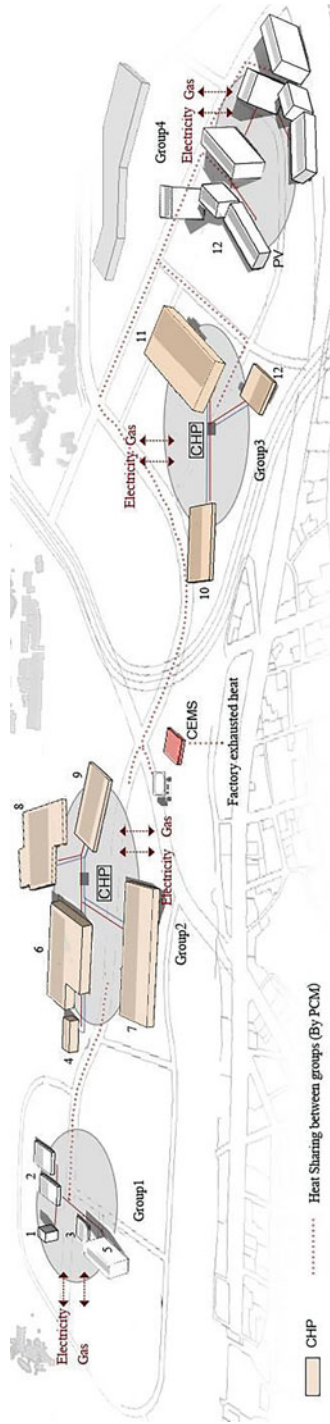
Fig. 6.16 Image of community and district zoning

Table 6.2 Yearly energy consumption and the peak load

Group		Group1	Group2	Group3	Group4	Community
Function		Office&hotel	Commerce	Education	Residence	
Building area(m²)		30555	17545	28692.3	72212	149004.3
Roof area(m²)		24358	5420	13342.9	7146	50266.9
Yearly energy consumption	Electricity (GWh)	2.77	7.85	1.50	0.98	13.61
	Electricity*(GWh)	2.51	5.13	0.68	1.49	9.07
	Cooling (TJ)	6.89	24.38	5.05	2.89	39.21
	Heating (TJ)	2.79	3.54	5.75	4.14	16.21
	Hot water (TJ)	3.37	2.85	0.00	8.91	15.13
Peak (kW)	Electricity	598	2260.8	471	1652.4	3313
	Electricity*	532.8	2048.4	344	1634.4	3037
	Cooling	1484.00	5155.50	1920.20	1719.55	9085.60
	Heating	458.76	1808.89	2750.25	566.86	5134.89
	Hot water	275.42	535.85	0.00	1360.87	1622.77

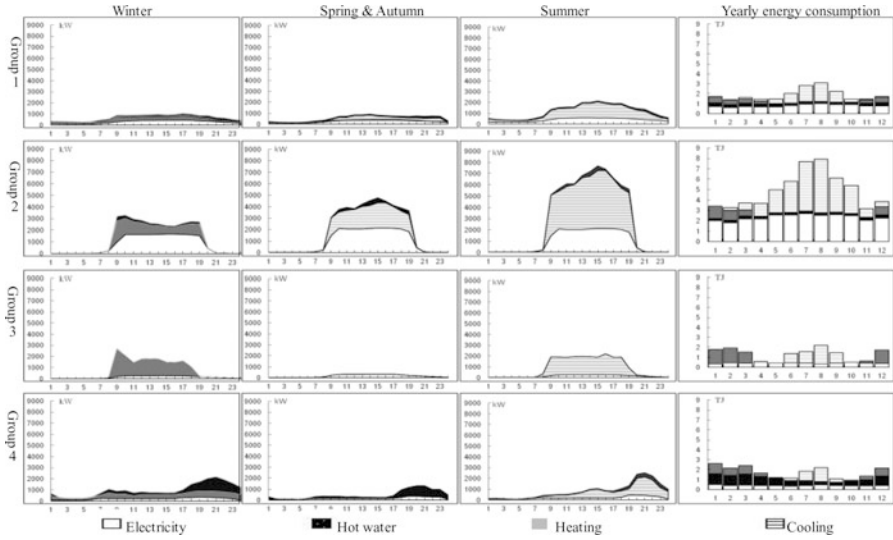Electricity* : The electricity demand excluded PV

Fig. 6.17 The district energy consumption

Figure 6.17 described the detailed hourly load profiles for every group in summer (August), winter (January), spring, and autumn (May). The energy consumption profile firmly related with the building function.

I) Group 4 is the residential area; thus, the peak of the energy consumption comes during the night. Group 1 also has considerably higher energy consumption compared with group 2 and group 3, because there is a hotel in the group.
II) The commercial group (group 2) has a higher energy consumption during the day, but with almost no energy consumption during the night.
III) The hot water load is higher in residential group (group 4), but lower in group 2 and group 3.

6.5.2 FEH Load

1. Investigation and estimation of the factory exhaust heat

Kitakyushu is one of the most important industrial cities having a large area of industry. Thus, the CO_2 emission from the factories is more serious than the average level of the whole country. In that case, the city will try to reuse the potential energy from the factory exhaust heat, aiming to construct a low carbon society combining industry, school, government, and residential environment together.

To estimate the exhaust heat of the whole city, the research put forward a questionnaire to all the factories and industries in Kitakyushu. The investigation

includes 170 factories and 213 industries. It covers the equipment, temperature, working hours, and so on. All the factories that been reported by the Kitakyushu were included in the estimation in this research.

6.5.2.1 Methods

In Japan, around 90% of the exhaust heat is discharged as gas. Therefore, in this research, the estimation of the exhaust thermal reserves is estimated by gas.

(1) Maximum exhaust heat.

From the result of the questionnaire, the factory measured values can offer the maximum gas discharge amount and the discharge temperature. The maximum exhaust heat energy can be calculated as below:

$$E_{max}^{RH} = V_{max}^{RG} \times T_{max}^{RG} \times C_g$$

E_{max}^{RH} (KJ/h) is maximum hourly exhausted thermal energy.
E_{max}^{RH} (Nm^3/h) is maximum hourly gas discharge amount.
E_{max}^{RH} (°C) is gas discharge temperature.
Cg (KJ/N m3·°C) is the specific heat capacity of gas (1.356 KJ/N m^3).

(2) The ratio between the maximum exhaust heat and the normal exhaust heat.

The facilities with exhaust heat will measure the hourly exhaust gas including the discharge amount and the temperature. It takes out 2 or 6 years a time depending on the scale of the facility. This research uses the last record of measured value and set the mean value as the normal value.

Conversion coefficient between the maximum value and the normal value can be defined like the following:

$$\alpha_V = \frac{V_{max}^{RG}}{\overline{V}_{real}}$$

$$\alpha_T = \frac{T_{max_x}^{RG}}{\overline{T}_{real}}$$

α_V is the conversion coefficient between the maximum exhaust gas amount and the normal exhaust gas amount.
$\overline{V}_{real}$ is the mean value of the last measured data of discharged gas amount per hour.
α_T is the conversion coefficient between the maximum exhaust gas temperature and the normal exhaust gas temperature.
$\overline{T}_{real}$ is the mean value of the last measured data of discharged gas temperature.

The result of α_V and α_T are listed out in Figs. 6.18 and 6.19. The mean values are set as the conversion coefficient
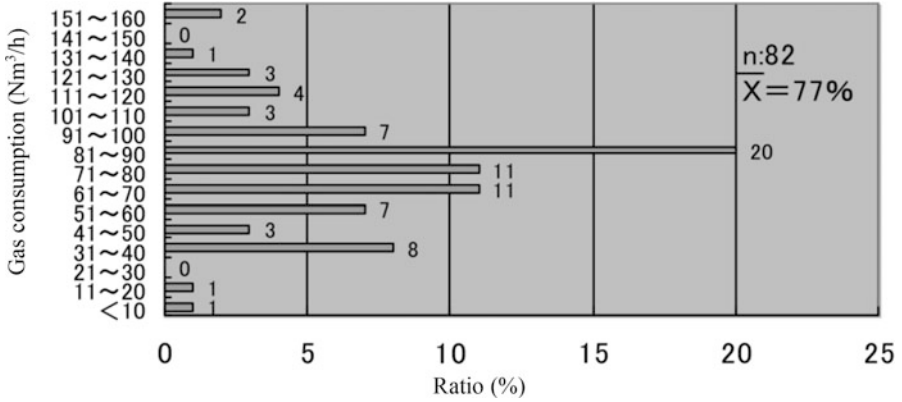
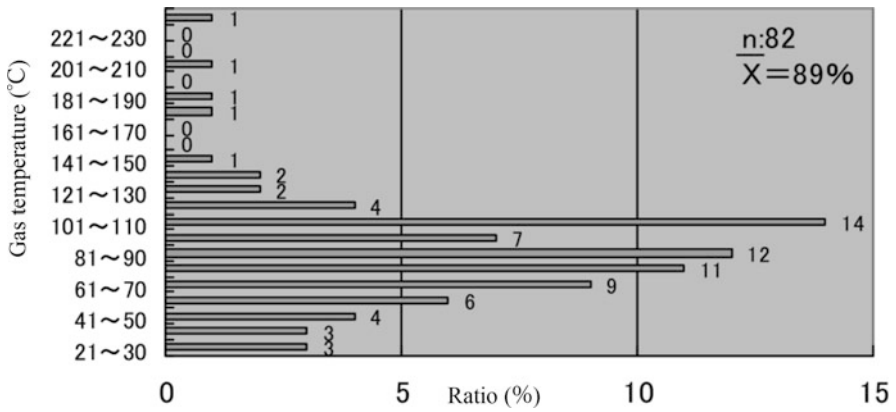**Fig. 6.18** Conversion coefficient between the maximum and the normal exhaust gas amount

Fig. 6.19 Conversion coefficient between the maximum and the normal exhaust gas temperature

$$\alpha_V \text{ polt } (\overline{\alpha}_V = 0.77)$$

$$\alpha_T \text{ polt } (\overline{\alpha}_T = 0.89)$$

Therefore, the exhaust heat energy can be estimated as follows:

$$E^{RH} = V_{max}^{RH} \times \overline{\alpha}_V \times T_{max}^{RG} \times \overline{\alpha}_T$$
$$= V_{max}^{RH} \times 0.77 \times T_{max}^{RG} \times 0.89$$

E^{RH} (KJ/h) is the estimated exhaust heat per hour.

Table 6.3 The setting for working hours

Building category		Working hours(h)
Factory	the factory above 500cal/h	24
	Others	8
	Hospital, hotel	24
	Public Waste disposal facilities	24
Industry	Nursing homes for elders	24
	Shopping centers	12
	School	12
	Others	8

(3) The setting for working hours.

The working hours will be estimated according to the questionnaire among the factories. The investigation includes 170 factories and 213 industries, and the questionnaire recovery rate is 37.6% for factories and 20.3% for industries.

According to the result, the working hours can be set as in Table 6.3. The average working ratio can be set as 0.7.

(4) The estimation for yearly rejected heat energy.

The yearly rejected heat energy for every factory can be calculated as below:

$$E_{yearly}^{RH} = E_{\max}^{RH} \times 0.77 \times T_{\max}^{RG} \times 0.89 \times C_g \times 24h \times 356d \times 0.7$$

E_{yearly}^{RH} (KJ/h) is yearly gas discharge amount.

6.5.2.2 The Estimation Result of the Exhaust Heat

This survey covered 1552 facilities that have exhausted heat in Kitakyushu, among which 1412 were used for the estimation.

There are 7 districts in the city, and the 1412 factories are in the whole city. As the result of estimation, the yearly rejected heat energy is about 18,000TJ. Figures 6.20 and 6.21 show yearly rejected heat energy of every district.

Another important input to the energy system is the reutilization of the FEH. It is collected by PCM system and used in the community for heating, cooling, and hot water. The study selected out the four potential factory resources (within 20 km) [10]. Usually, the temperature for FEH is higher than 300 °C and daily exhaust heat is around 38.9 GJ. The tank type with the capacity of 1.4 MWh will be introduced into the system. As this research only discussed the environmental effect of the PCM system, thus it is supposed that there are enough tanks for collecting all the exhaust heat (the heat of the factory and the unused CHP recovery heat).
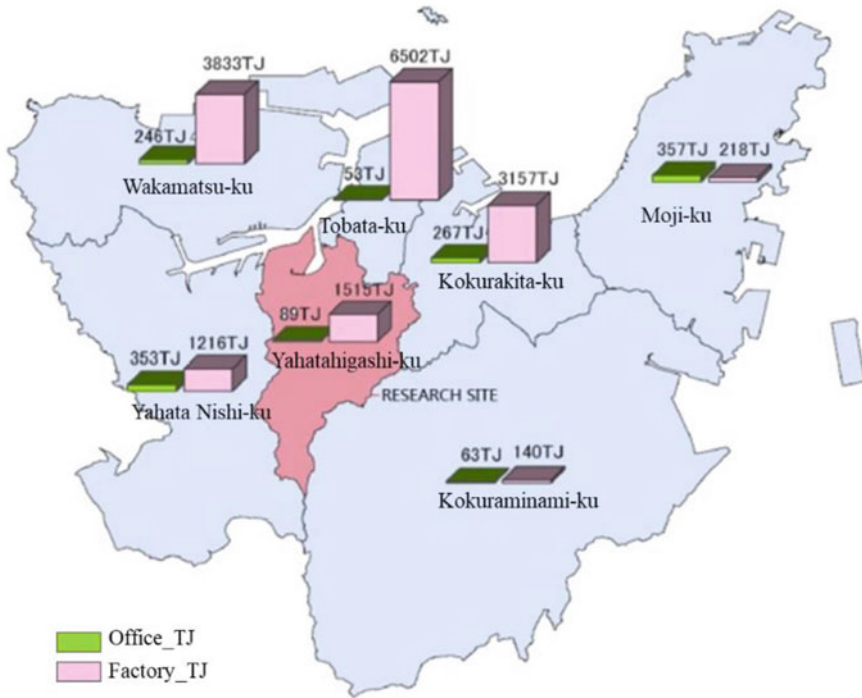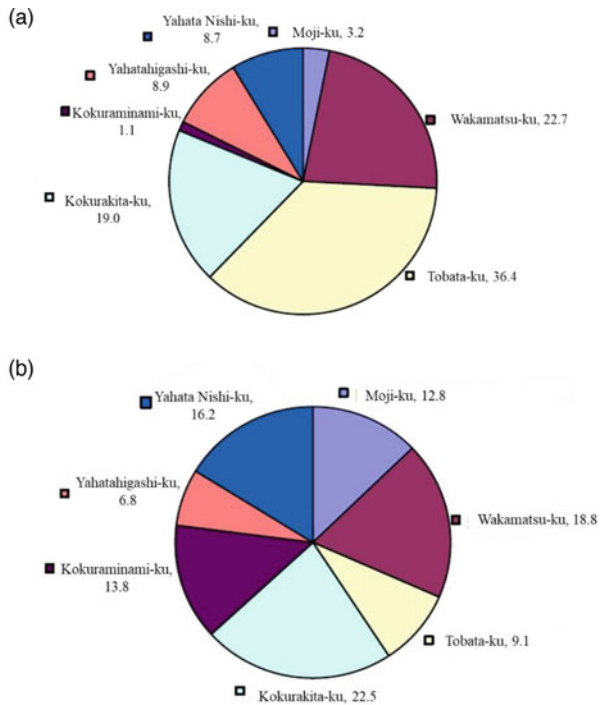
Fig. 6.20 Yearly rejected heat energy of every district

Fig. 6.21 The distribution of exhaust heat reserves and facilities by district (**a**) The exhaust heat reserve proportion (**b**) The exhaust heat facility proportion

Table 6.4 Technical parameters of system

Facility		Parameter	COP
Grid		η	0.35
CHP Plant			
Gas Engine (GE)	Electricity Generation	η_e	0.3
	Heat Recovery	η_{rec}	0.45
Fuel Cell (FC)	Electricity Generation	η_e	0.4
	Heat Recovery	η_{rec}	0.3
Hydrogen Fuel Cell (HFC)	Electricity Generation	η_e	0.48
	Heat Recovery	η_{rec}	0.42
Absorption Chiller		COP_{ac}	1.1
Heat Exchanger(H-EX)		COP_{he}	1
Boiler		η_{b1}	0.8
Multiple Air-conditioning System	Cooling	COP_1	4
	Heating	COP_2	3.9
Room Air Conditioner	Cooling	COP_1	3.22
	Heating	COP_2	2.83
PCM system		η_{rec2}	0.9

6.5.3   DEG Technologies and District Energy System

This district is the demonstration area that the latest technologies are expected to introduce into the area. The smart community has also undertaken the Kitakyushu Hydrogen Town project. The project is the world's first attempt to use a pipeline recycling the hydrogen generated in the iron manufacturing and operating the fuel cells as an energy supply to the district. The demonstration testing is processed jointly by Fukuoka prefectural and city gas utilities [13]. The pipeline is connected with the hydrogen station and hydrogen fuel cells that are installed in buildings in this district. These fuel cells generate electricity by combining hydrogen and oxygen. Table 6.4 shows DEG technologies assumed in this study and their properties, including gas engine (GE), fuel cell (FC), hydrogen fuel cell (HFC), and PV. All equipment is city gas fired.

6.5.4   Setting of Cases

In order to investigate the effect of technologies in the DRN, the following cases are assumed for analysis.

Base case: conventional system. Base case indicated conventional energy supply system. The electricity load is satisfied by grid. The buildings also used air conditioner for heating and cooling. Commercial buildings and office and public buildings use multiple air-conditioning systems, and residential buildings use room air conditioner. The hot water load is satisfied by gas boiler fired by city gas.
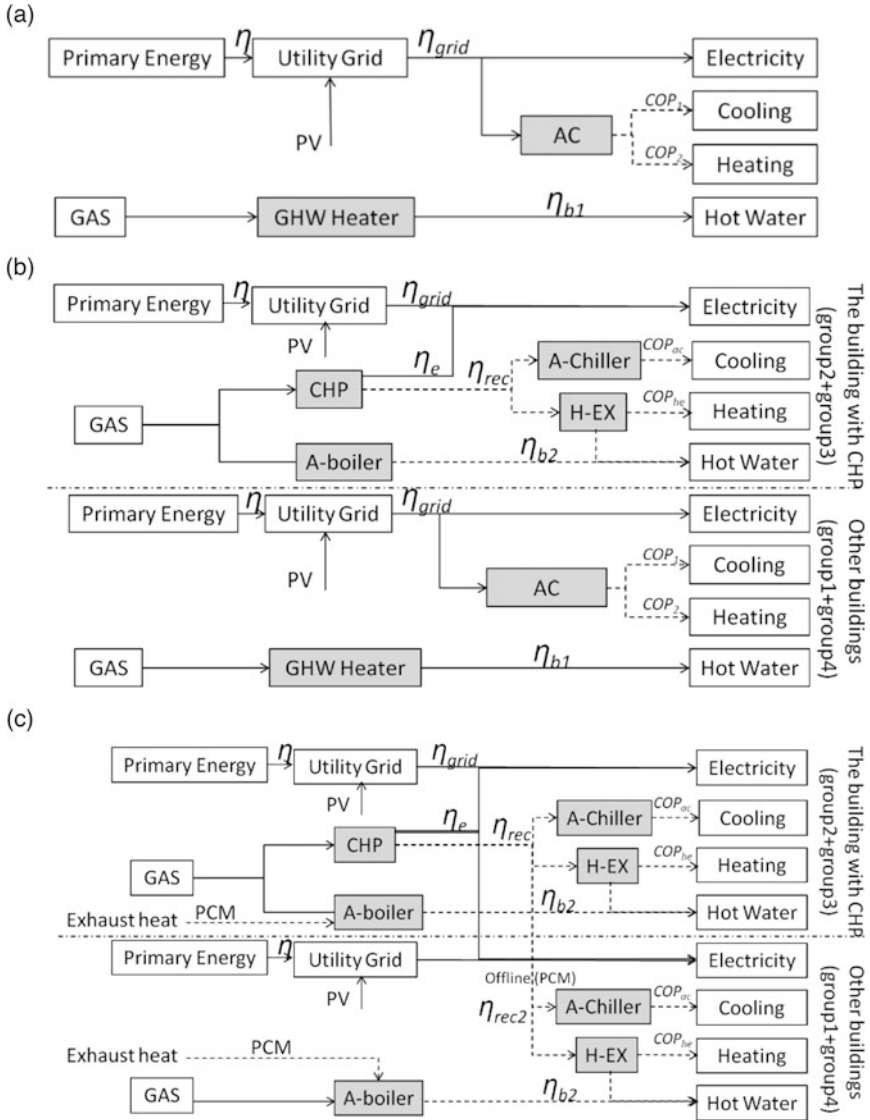
Fig. 6.22 Case setting

Case 1: The conventional system combined with PV systems. In this case, the community still keeps the conventional system, but facilitated with PV. The system is as in Fig. 6.22a. The electricity will be supplied by PV system, or by grid, or by both. The electricity from the PV system will be used by the buildings themselves, and remaining electricity will be sent back to the grid.

Case 2: Individually introduced DEG systems, displayed in Fig. 6.22b. In case 2, the CHP plants with GE are introduced in group 2 and group 3. The CHP plants and PV systems can satisfy the electricity load of these two groups. The thermal load can also be supplied by the recovery heat of the CHP plants and the deficiency supplemented by gas boiler. In this case, the electricity and recovery heat of the CHP plants cannot supply to other groups or return back to the grid. Therefore, the NCHP groups still get electricity from the PV and grid, kept as the conventional system.

Case 3: DRN system without using factory exhaust heat, described in Fig. 6.22c. In the DRN system, the community uses the same DEG technologies with case 2, but controlled and managed by CEMS. Under the CEMS, the electricity produced by the CHP plants cannot only be used for the CHP group but is also supplied to the NCHP group. The recovery heat of the CHP group will be used in the CHP group first and then recycled by the PCM system. The CEMS distributed the heat that is stored in the PCM system with thermal shortage and surplus profile of every group.

Case 4: DRN system with the utilization of the FEH, as in Fig. 6.22c. Besides the technologies and DRN system that are assumed in case 3, case 4 also makes use of the FEH by PCM system. The PCM system collects the exhaust heat from the factory resource that is set in part 3 and transports it to the CEMS in the community. Besides the surplus CHP recovery heat, this part of heat will also be distributed by CEMS.

Case 5 and case 6: The DRN system with the CHP plants of FC and HFC. Beyond the DRN systems built in case 4, case 5 introduced the CHP plant of FC and case 6 introduced HFC.

## 6.6   Results and Discussions

6.6.1   The Effect of Electricity Sharing in DRN System

Figure 6.23 is the electricity balance in the community with the individually introduced DEG systems (case 2) and the DRN system (case 3). Both cases use CHP plant with GE and PV. The comparison between the two cases can show the effect of the electricity sharing between them. It can suggest that PV system can provide 35% of the community electricity consumption and the individual CHP plant can produce 41% electricity. By electricity sharing, the CHP group can offer 2GWh electricity to the non-CHP group, which occupied 52% of their electricity consumption. As a whole, the community can produce 58% of the electricity by CHP, and only 7% from the grid, while the individual system needs 24%.

As we know, the electricity produced by DEG has less energy loss during the electricity delivery. Therefore, the system can save more energy as it gets less electricity from the grid. In the DRN system, the CEMS can operate the CHP plants and distribute the electricity to the whole community. Therefore, it will increase the output and working hours of the CHP plant and reduce the electricity from the grid.

The electricity sharing under the CEMS can balance the electricity consumption between the different groups, making the system more independent and reliable.

Fig. 6.23 Yearly electricity balances of case 2 and case 3
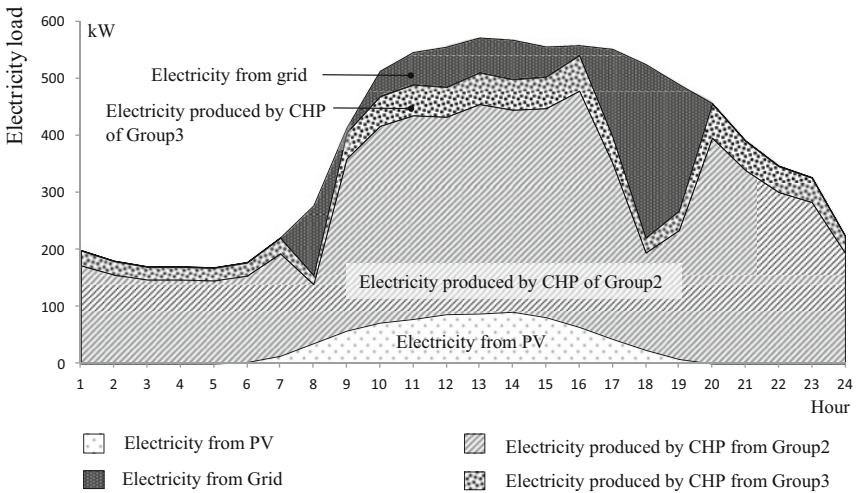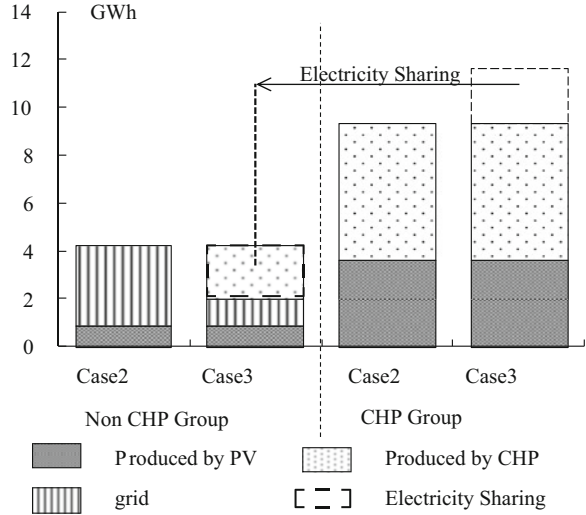
Fig. 6.24 Daily electricity balance of group 1 (summer)

Figure 6.24 displayed the daily electricity balance in group 1, taking summer as example. The buildings in group 1 have small roof areas that the PV can only offer a small part of the electricity. Compared with group 4 (the other NCHP group), group 1 has higher electricity shortage, thus preferentially getting electricity from the CHP group. CHP can satisfy most of its electricity demand. Especially, during the night, the electricity load is low in commercial buildings that the electricity demand in group 1 can be satisfied by CHP only.

The electricity sharing used in DRN system can shift the electricity demand from the peak. Just as Fig. 6.24 suggested, without CHP plant, the peak hour should come during the noontime, but now it shifts to 8 o'clock in the morning and 18 o'clock in the afternoon. Further, from the city level, the less relay on the grid will alleviate electricity shortage especially during the peak hours. That means with the DRN, the city can smooth out the electricity fluctuation.

6.6.2   The Effect of Heat Sharing in DRN System

The DEG with CHP plants not only reduce the energy loss but can make use of the recovery heat as well. In case 2, the individual CHP system can only use the recovery heat by the CHP group itself. However, under the CEMS, in case 3, the DRN system can distribute the recovery heat to other group with the PCM system. In that case, it improved the utilization rate of the recovery heat. As Fig. 6.25 illustrated, the individual CHP has 37.9GWh recovery heat every year, and 31.1 GWh is used for thermal consumption in CHP group. In DRN system, the yearly CHP recovery heat is 47.3 GWh, among which 6.4G Wh heat is offered to the NCHP group. This part of heat occupied 33.8% of heat consumption in NCHP. Under this condition, 85% of the CHP recovery heat can be reused which possessed 68.8% of the community heat demand.

Figure 6.26 illustrates the daily heat balance in the community, taking the wintertime as example. The plus value means the heat surplus of each group. Group 2 and group 3 are the CHP groups, and their heat surplus means the remaining

Fig. 6.25 Yearly heat balances of case 2 and case 3
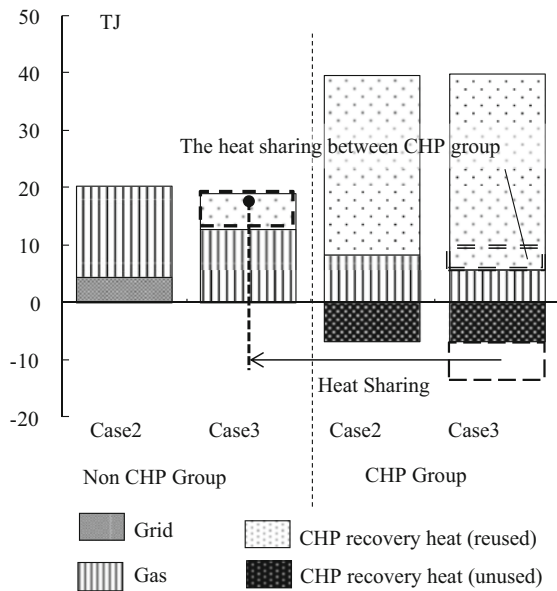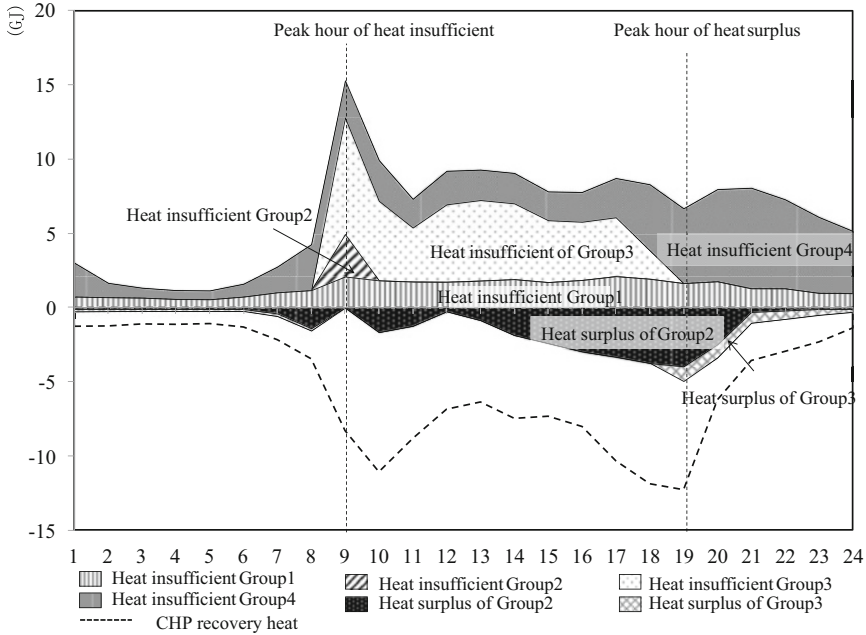
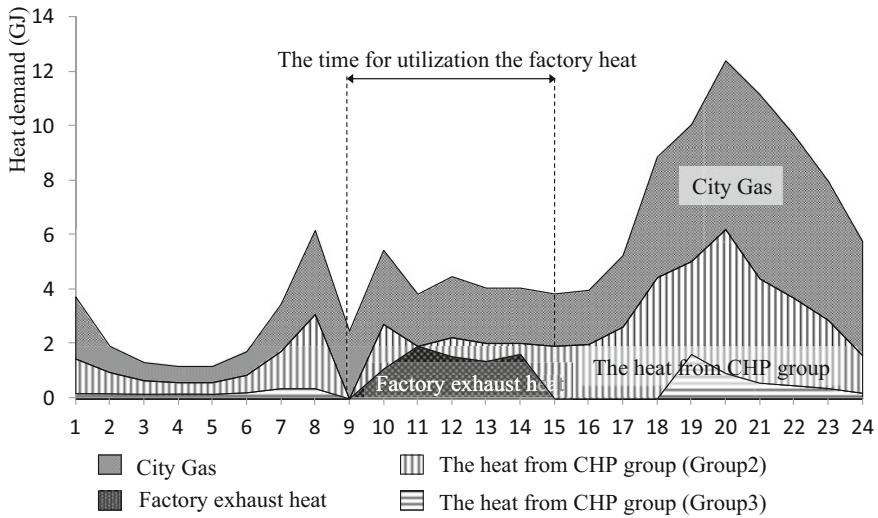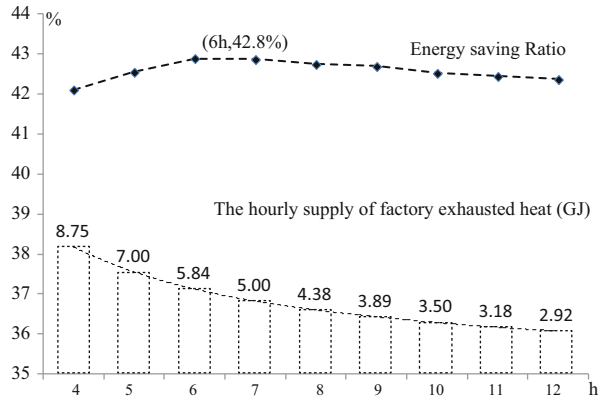**Fig. 6.26** Daily heat balances of the community

heat after their own utilization. PCM system can collect this part of heat which is used for heat supply in other groups. The minus part means the heat shortage. For group 2 and group 3, it means the heat deficiency after utilizing the CHP recovery heat. Figure 6.26 can suggest that the first peak of the heat shortage comes on 9 o'clock in the morning, and the peak of the heat surplus comes on 19 o'clock. Group 2 and group 3 have no heat demand from 19 o'clock to the next 9 o'clock; thus, during this time, all the CHP recovery heat will be supplied to NCHP group. From the 9 o'clock to 19 o'clock, group 3 has the largest heat shortage; thus, the stored heat in the PCM system will be preferentially supplied to group 3. That means the heat sharing is not only between the CHP group and NCHP group but also between the CHP groups. After the CEMS collected the heat and stored it in the PCM system, it only distributes the heat according to the heat insufficient volume.

6.6.3 The Effect of Using Factory Exhausted Heat

Until now, the city of Kitakyushu still has 1412 factories and industries, which have exhaust heat. The existing research put forward questionnaire to all the factories, estimating and setting up a database by GIS for the yearly exhaust heat. As a result, the yearly exhausted thermal energy is about 18,000TJ.

Fig. 6.27 Energy saving ratio and the supply span of factory exhaust heat

Fig. 6.28 Heat balance considering factory exhaust heat (group 4, winter)

For this community, four factories were set as the resources, and the total yearly heat amount that can offer to the community was 14.2 TJ (38.9GJ per day).

In this research, it is set that exhaust heat will be averagely supplied to the community from the first peak hour in the set time range. Figure 6.27 is the relationship between time range and the heat volume, as well as the energy saving result. It can suggest that in this case, 6 hours is the optimal time range and it can cut 41.4% of primary energy beyond the PV and CHP system.

Figure 6.28 is the daily heat balance with the utilization of the factory exhaust heat, taking group 4 in the wintertime as example. During the daytime, group 3 has higher heat load that the factory exhaust heat will firstly be supplied to group 3. However, the factory heat can still afford on part of the heat load of group 4. During the night, group 2 and group 3 have no thermal demand that the stored heat will firstly offer to group 1, but still another part can afford almost half of the heat demand in group 4.
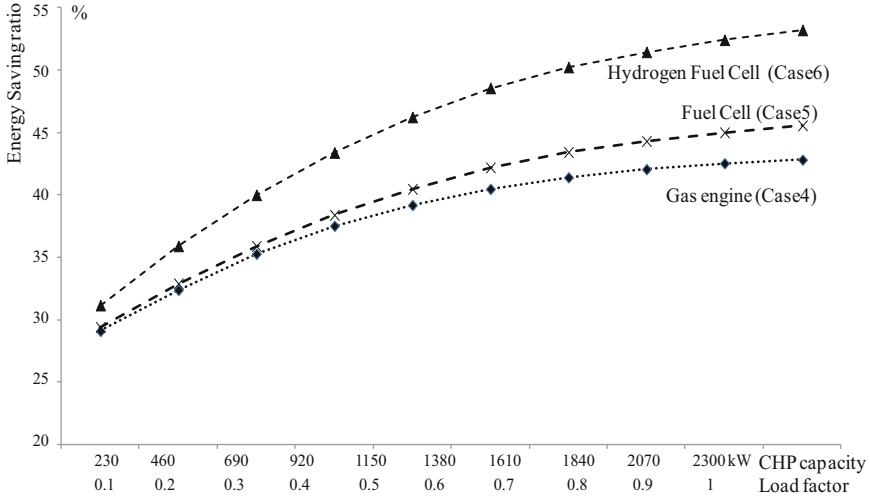
Fig. 6.29 Energy saving ratio with different kinds of CHP plant

6.6.4 The Effect of Introduction of Different CHP Plant

As the techniques of CHP plant improved, the environmental performance of the system changed as well. The gas engine and the fuel cell have already been widely used in Japan. As a trial project, the community introduced hydrogen fuel cell. Figure 6.29 is the energy saving ratio of these three kinds of CHP plant. The fuel cell and gas engine had similar effect when the capacity is low, but after 1000 kW, the fuel cell improved obviously. The hydrogen fuel cell had a higher efficiency on both electricity generating (48%) and heat recovery (42%); thus, the system can reach an optimal energy saving ratio of around 53%.

6.6.5 The Assessment from the Community Side

Figure 6.30 is the energy saving ratio for various cases. The PV system can cut off 22.6% primary energy consumption. The individual CHP plants and the PV system can totally cut 30.6% primary energy consumption. Based on this system, the execution of the DRN system can cut off 38.2%. By introduction of hydrogen fuel cell, the community can cut off 53.1% primary energy consumption as its target.

Figure 6.31 is the low carbon ratio for every technology. By introducing the PV system and the CHP plant (gas engine), it can cut off 29.4% of the carbon emission. The networking CHP system can reduce energy consumption and cut off another 7% carbon emission. Besides these, the reusing of factory rejected heat energy can cut off 41.1% CO_2 emission. With the introduction of fuel cell and hydrogen fuel cell, it is proved that the community can get 51.8% CO_2 emission reduction ratio.
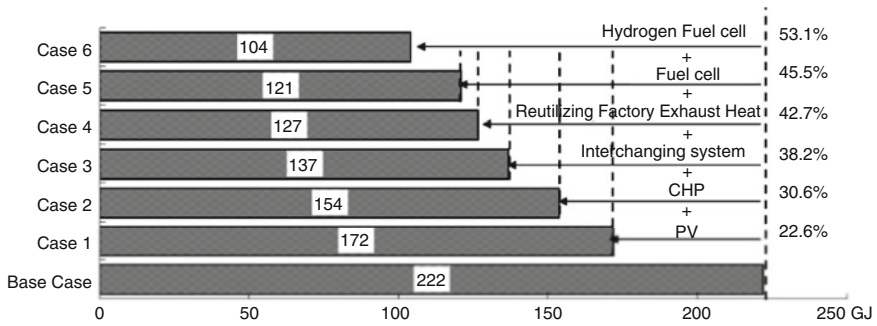
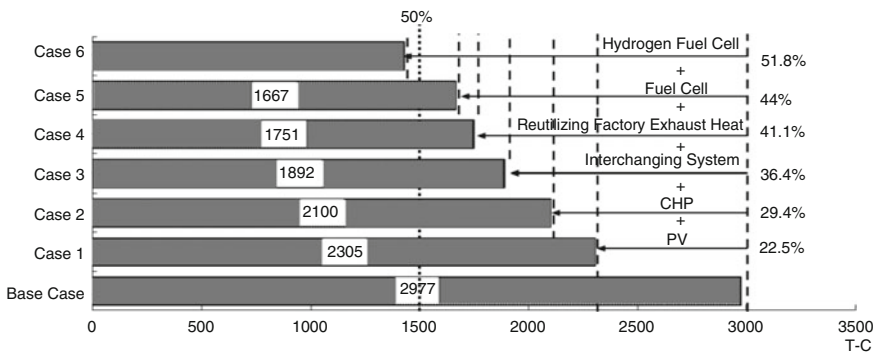**Fig. 6.30** The energy saving ratio for various cases

Fig. 6.31 Yearly CO_2 emissions for cases

6.6.6 Conclusions

This chapter proposed a DRN energy system model for smart community in Japan. One innovation is that the model not only has a smart grid but also has a smart heat energy supply chain by PCM system. The PCM system controlled by CEMS conducted the heat sharing between buildings. In that way, it can maximize onsite use of CHP recovery heat. Further, this model promoted a collaborative energy utilization mode between the industrial sector and the civil sector. The introduced PCM system will also collect the exhaust heat from the nearby factory. It not only made use of the untapped energy but also cuts off the CO_2 on the factory side (the exhaust heat) as well. In addition, the research chose the smart community in Kitakyushu as case study and executed the model. The simulation and the analysis of the model is embodied by temporal perspective of the low carbon techniques in Japan, including nature and untapped resource, CHP plants, and the PCM system. The result suggests not only the environmental effect of different technologies but also the potential of its overall performance.

(1) The DRN energy system proposed in the study is a treelike hierarchical model that consists of BEMS, ES, and CEMS. The CEMS can dispatch the energy, including heat and electricity in the district, by the information received from the ES. The electricity sharing between the groups can improve the working hour and output of the CHP system. In that case, the distributed energy system can satisfy 95% of electricity consumption by itself. It enhances the reliability and independence of the energy system and shifts the energy consumption away from the peak hour as well. Heat sharing can also enhance the independence of the energy system and satisfy 68.8% of the thermal demand by CHP recovery heat.

(2) The CHP plant is widely used and developed quickly in Japan. There are different kinds of CHP plants, as gas engine and fuel cells. They have different characteristics and different electricity generation efficiency and heat recovery efficiency. The latest hydrogen fuel cell, firstly under trial in this district, is the new kind of CHP plant that can obviously improve the environmental effect of the system.

(3) In general, the introduction of nature energy resource (PV) can cut 22% of the primary energy consumption and CO_2 emission. The introduction of CHP systems can cut around 30.6% primary energy consumption and CO_2 emission. Beyond that by DRN control, the district energy sharing can cut 38.2% primary energy consumption and 36.4% CO_2 emission. The use of factory exhausted heat and the development of the CHP plant can help the district to finally reach the target: cut more than 50% of the primary energy consumption and the CO_2 emission.

The area energy network will be widely used toward carbon neutral, with the district electricity and heat network. The offline heat transport system, which is not needed in the infrastructure investment, can be a useful way for heat sharing and waste heat utilization in low-density area.

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