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Implementation of expansion planning in existing district energy system: A case study in China

Jin Hou[a], Peng Xu[b,*], Xing Lu[b], Zhihong Pang[b], Yiyi Chu[b], Gongsheng Huang[a]

[a] *Department of Architecture and Civil Engineering, City University of Hong Kong, Kowloon 999077, Hong Kong*
[b] *Department of Mechanical and Energy Engineering, Tongji University, Shanghai 201804, China*

HIGHLIGHTS

- The methodology of expansion planning of existing district energy system is presented.
- Operational efficiency is improved from the demand side and supply side.
- The method to improve operational efficiency through improvement of secondary load structure is proposed.
- The new evaluation system of the whole district is proposed and used to evaluate and compare multiple expansion schemes.

ARTICLE INFO

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Expansion planning
Existing district energy system
Load structure
Evaluation system

ABSTRACT

Traditional energy planning methods are mostly related to newly-built area. However, in most already-built regions, the existing district energy systems (DESs) need to be ameliorated due to insufficient capacity and low efficiency. This paper investigates the methodology of expansion planning, which can offer planners a viable way to expand existing DESs. The term “expansion” aims to increase the supply capacity of the energy forms, e.g., steam, hot water and electricity, which cannot be accessed from national or urban energy supply network, and meanwhile increase energy utilization efficiency and cut CO_2 emission. Three parts of the methodology, including problem analysis in current DESs, demand side analysis and the existing DES expansion, are introduced in this paper. New concepts of load structure and evaluation system of the whole district are proposed in this methodology. A case analysis of Ningbo Hi-Tech District, China is conducted to shed light on the application of this method.

1. Introduction

With the rapid rate of economic and industrial growth in developing countries, the consumption of fossil fuel and carbon emissions are increasing significantly [1,2]. In order to solve this problem, better schemes and more efficient technologies should be applied to energy systems on different temporal and spatial scales. District energy system (DES), accompanying with national or urban energy supply, utilize all available resources to produces energy of multiple forms such as steam, hot water and electricity and thus satisfy the needs of all customers. Therefore, optimal DES planning, as a critical part of a city’s energy development strategy, can create great economic and environmental benefits [3], contributing significantly to the development of low-carbon cities.

Methods to implement DES planning have been proposed according to different stages of district development, including community master plan (CMP) [4,5], community regulatory plan (CRP) [4,6], community site plan (CSP) [4,6] and architectural design (AD). Those methods can be divided into two categories: top-down method and bottom-up method [7]. The former one is mostly used in the stages of CMP and CRP while the latter one in the stages of CSP and AD. The top-down method guides and regulates DES planning on the basis of detailed implementary measures and quotas of upper policy which are formulated according to the statistical data of projects of different regions. The BRE environmental assessment method and rating system for communities (BREEEAM Communities) [8,9], Leadership in Environmental and Energy Design for Neighborhood Develop Rating System (LEED-ND) [10] and the comprehensive assessment system for built environment efficiency (CASBEE) [11] are standards or guidelines used as energy policies in this method. Compared with the top-down method, the bottom-up method is more contingent on technologies to guide the planning. Bottom-up method consists of load forecast,

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[*] Corresponding author at: Tongji University, No. 4800 Cao'an Road, Shanghai 201804, China.
E-mail address: xupeng@tongji.edu.cn (P. Xu).

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Nomenclature

Acronyms

AC	air conditioning
AHU	air handling unit
B-P	phase-back pressure turbine
CHP	combined heating and power
COP	coefficient of performance
CSP	community site plan
DCHP	distributed combined cooling, heating and power
DES	district energy system
EAC	electrical air-conditioner
GICE	gas internal combustion engine
GT	gas turbine
HVAC	heating, ventilation, and air conditioning system
IRP	integrated resource planning
LARU	Li-Br absorption refrigeration unit
VRV	variable refrigerant volume
AD	architectural design
ASHP	air source heat pump
CHE	central heating equipment
CMP	community master plan
CRP	community regulatory plan
CW	cold water
DSM	demand side management
E-C	phase-extraction condensing
GSHP	ground source heat pump
HRSG	heat recover steam generator
HW	hot water
KF	Kefeng
S-S-C	straight stream condensing
WSHP	water source heat pump

Variables

D	secondary load, MJ
e	load density of buildings, MJ/m^2
E_{ind}	industrial load of base year, MJ
Ef	CO$_2$ emission coefficient
M_{CO_2}	emission of CO$_2$, ton
S	floor area, m^2
T_{burn}	theoretical combustion temperature, K
T_{hd}	indoor dew point temperature in winter, K
T_{st}	saturation temperature under certain steam pressure, K
T_s	supply water temperature, K
η	conversion efficiency
ε	energy saving performance, MJ/m^2
E	energy or load, MJ
E^{Ca}	rated capacity, MJ
ECC	exergy conversion efficiency
EX	the amount of exergy, MJ
Q	output energy, MJ
T_0	reference temperature, K
T_{cd}	indoor dew point temperature in summer, K
T_r	return water temperature, K
W	input energy, MJ
Λ	energy quality coefficient
γ	annual growth rate of production

Subscripts

	boiler
cw	cool water
eg	national grid
f	fuel
hn	urban heating network
hw	hot water
min	minimum value
sf	supply of fuels
wc	conventional water chilling unit
c	cooling
e	electricity
es	energy storage
h	heating
hp	heat pump
max	maximum value
re	renewable energy resource
st	steam

available energy resource assessment and energy supply system optimization. Three methods are mostly used to forecast building energy consumption, including statistical regression forecast method, building performance simulation method and load index method [12]. A region's available energy resources basically come from the national grid, city gas network and renewable energy sources. The assessment of regional available energy resources usually refers to the assessment of renewable and low-grade energy resources since they are limited. Natural conditions, technical feasibility, economical efficiency and influence on the environment are factors considered in the assessment [13–16]. In terms of the optimization of an energy system, scholars tend to adopt mathematical models to obtain the minimum/maximum target and optimum solution with design constraints, such as carbon footprint constraints [17,18]. Those mathematical models are usually solved with a programming software, such as Linear Interactive and General Optimizer (LINGO), the General Algebraic Modeling System and Matlab toolbox.

It can be observed from the introduction above that both top-down method and bottom-up method are mainly used in the cases of newly-built area. However, planning methods are also needed for existing DESs in already-built regions. Because of the outdated concept and technologies used in energy supply systems and on demand side, existing DESs usually operate with low efficiency compared with newly planned DESs. Besides, with the district development, the existing DES fails to satisfy the future energy demand, especially heating, cooling and domestic hot water which are not supplied by national or city energy supply network. For these reasons, it's necessary to expand existing DESs. The expansion aims to increase the supply capacity of the energy forms, e.g., steam, hot water and electricity, which cannot be accessed from national or urban energy supply network, and meanwhile increase energy utilization efficiency and reduce CO$_2$ emission. Other than the planning of newly-built DES, the expansion planning of existing DES is different in two aspects: (1) system and equipment operation in low efficiency are transformed; (2) the configuration of the original system is well taken into account in the expansion planning project. In view of the very deficiency of related study, it's necessary to propose a systematic methodology to direct and regulate DES expansion planning.

In this study, we present the planning methodology for expansion planning in existing DESs based on the concept of integrated resource planning (IRP) [19], which attaches great significance to the integration of varieties of energy-saving technologies and highly advocates the use of renewable energy sources and demand side sources This methodology includes four parts: problem analysis in current DES, demand side analysis, available energy resource assessment and the existing DES expansion. In addition to new demand forecast, energy conservation and load properties improvement are included in the demand analysis part, in which the new concept of load structure enhancing is put forward. In the expansion of existing DES, the optimum expansion scheme is selected by evaluating and comparing several schemes, considering the constraints from the original system configuration, which results in a limited number of independent variables. For evaluation and comparison, a new evaluation method has been proposed which takes both DES on supply side and terminals on demand side as the research object to comprehensively reflect the influence of a specific scheme on the energy consumption of the whole district. In the latter section of this paper, the methodology is applied to an engineering case, Ningbo Hi-Tech District, China, to illustrate the application of this methodology in detail.

2. Methodology

2.1. Framework

The first step of expansion planning for existing DESs is problem analysis. Then the expansion and improvement measures are taken from the demand side and supply side, namely demand side analysis, available energy resources assessment and the existing DES expansion. Since the assessment of available resources is the same as that of newly-built area, this part only demonstrates the analysis of the three other parts in detail. Fig. 1 illustrates the framework of expansion planning of existing DESs.

2.2. Problems existing in the current DES

Usually, there are two problems in existing DESs: insufficient capacity and low operational efficiency. In order to find out essential issues to help determine specific retrofitting and expansion scheme in the next parts, investigation and analysis of the existing DES should be done first. Areas involved include:

- Energy supply and demand situation in the existing district;
- Demand growth in the future and terminals;
- Configuration and operational efficiency of energy supply system;
- The balance of energy supply and demand in the future.

2.3. Demand analysis

As we know, the load size and properties have a direct impact on the configuration and operational efficiency of the energy supply system. Besides, the demand side with outdated energy consumption equipment and increasing energy demand, in already-built districts, has great renovation potential and need more demand side management (DSM). Thus, in expansion planning, demand analysis consists of three aspects: demand forecasting, energy conservation, and load properties improvement.

The concept of the demand side should be clarified prior to detailed explanation to demand analysis. The demand side usually refers to the total energy demand users including industries, buildings, etc. in district energy planning. Those users are regarded as a whole, namely ‘the

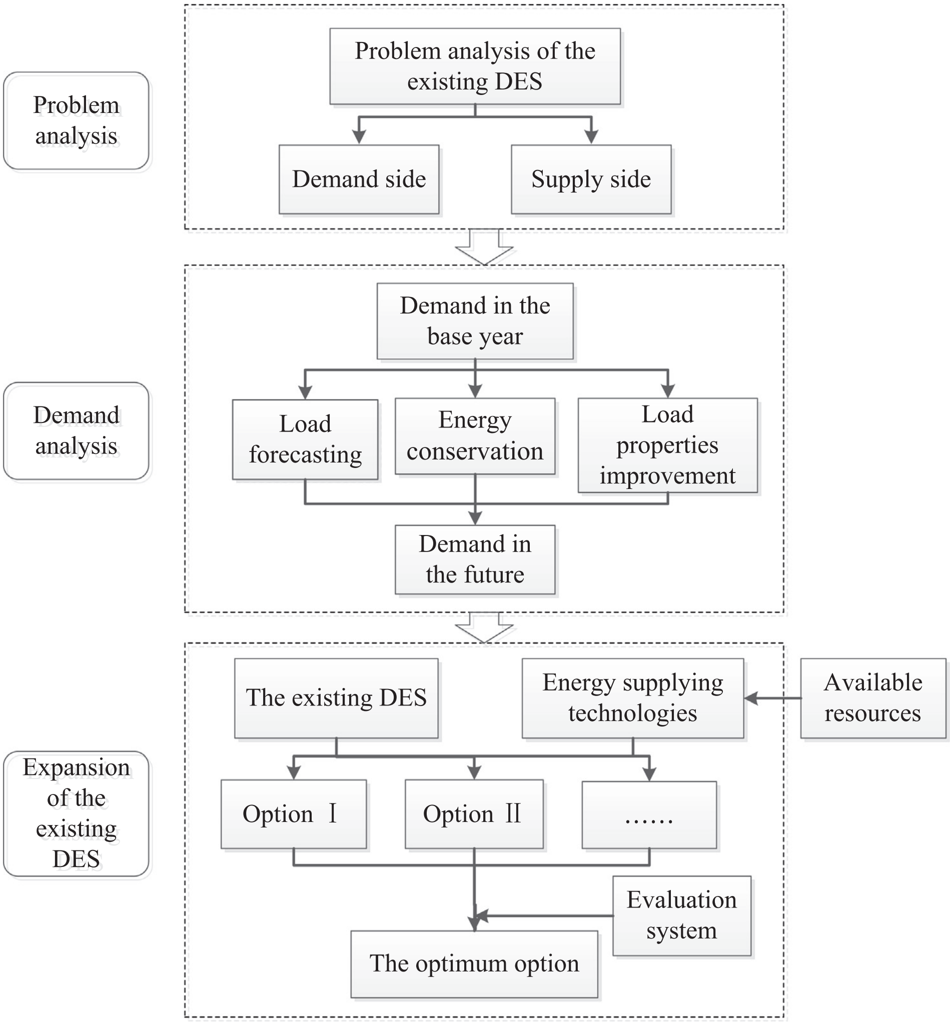


Fig. 1. Framework of expansion of the existing DES.

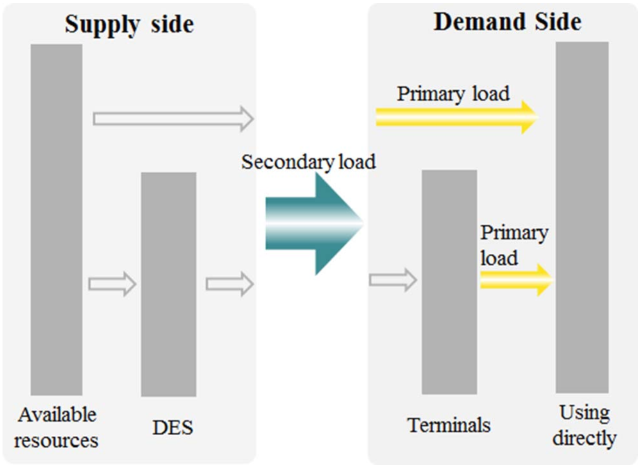


Fig. 2. Primary load and secondary load.

Table 1
Possible replacement of terminals.

Primary load	Terminal	Secondary load
Cooling load	EAC LARU AHU	Electricity Hot water/Steam Cold water
Heating load	EAC LARU AHU CHE	Electricity Hot water/Steam Electricity Hot water/Steam
Hot water	Electrical water heater Solar water heater Heat exchanger	Electricity Solar energy Hot water/Steam

demand side' and require energy supply from DESs or national or city energy supply network. We define this part of energy flow from supply side to the demand side as secondary load. However, secondary load is not always the direct need of human life and industrial production. Inside the demand side, terminal equipment such as air conditioners and water heaters are used to transform energy from the supply side to the forms which can be used directly, such as cooling, heating, and domestic hot water. We define this part of energy directly used in life and production as primary load. Definitions of primary load and secondary load are illustrated in Fig. 2. Since the purpose of demand analysis is to forecast and optimize the secondary load structure, and renovation and adjustment can be conducted on any object on demand side such as terminals, buildings, occupants' behavior.

Most common energy-saving strategies implemented in buildings include improved heating, ventilation, and air conditioning system (HVAC) [20], and improved insulation [21] and lighting [22,23], which can reduce the peak load and total demand, and so save energy and reduce the installed capacity of DES. The effect of energy conservation is determined by two factors: specific retrofit measures and the situation before retrofit. To predict the effect of energy retrofit measures and the demand in the future after retrofit, the method of building performance simulation, as has already been proposed, is highly recommended due to its convenience [24,25].

In terms of load properties improvement, temporal distribution is a main property of energy load [26]. The electricity price mechanism, load management and energy storage technology in DSM [27,28] can ameliorate the temporal distribution of primary and secondary loads by peak-load shifting. The significance of peak-load shifting is cutting down installed capacity, increasing utilization of energy supply and distribution system and so improving the operational efficiency.

Besides the temporal distribution, load structure is also a property of energy load. Load structure refers to the relative proportions of different categories of energy demand. For existing DESs, the supply capacities of different types of energy are fixed. Proper adjustment of secondary load structure can balance energy demand with the supply. Especially when combined heating and power (CHP) units or district combined cooling, heating and power (DCHP) units are adopted, an appropriate heat-to-electricity ratio in secondary load can maximum the operational efficiency since this ratio determines the waste heat utilization efficiency of power sets. Therefore, adjusting the secondary load to match the optimum load structure can save energy, and meanwhile ensure the demand and supply balance. Replacement of terminals on demand side is one of the methods to adjust secondary load structure. Although primary load structure determined by the requirements of life and industry is hard to change, a specific category of energy in primary load can be satisfied by different types of terminals. For example, the cooling load of a building can be satisfied by EACs, LARUs or cold water directly which consume different types of energy (secondary load) from the supply side. In this way, the replacement of terminals can ameliorate the structure of secondary load without affecting the energy usage of humans. The possible replacements are listed in Table 1. Of course, this method of improving secondary load structure by terminals replacement is only recommended when terminals replacement costs less than transform of energy supply systems.

2.4. Expansion of the DES

2.4.1. Scheme design

According to the IRP theory, the supply side of the DES should satisfy the energy demand of users as well as make full use of renewable energy and high-efficient energy conversion technologies. Therefore, the utilization of renewable energy and technologies conductive to increasing energy efficiency should be paid more attention in the expansion of DESs. At present, geothermal energy, wind energy, solar energy and biomass energy are the commonly used renewable energy sources in DESs. CHP and DCHP that have the benefit of energy stepped utilization, and energy storage systems that remove the coupling of energy demand and supply to some extent, are also widely utilized in DESs. Table 2 summarizes above technologies and their respective

Table 2
Characteristics of various energy supplying technologies.

Energy supplying technology	Energy input	Energy output	Characteristics
CHP/DCHP	Natural gas	Electricity, Heating/Cooling	1. Efficiency can be up to 60–90% 2. Cooling, heating and electricity are coupled
GSHP/WSHP	Electricity, Low-grade energy	Heating/Cooling	1. COP is higher compared with ASHP 2. Mitigate urban heat island effect
Energy storage system	Heating/Cooling	Heating/Cooling	1. Remove the coupling of energy demand and supply to some extent 2. Reduce the installed capacity of heating or cooling equipment 3. Reduce operational cost by staggering peak period
Renewable energy	Solar energy/Wind energy/Biomass	Electricity/Heating	Instability of energy supply

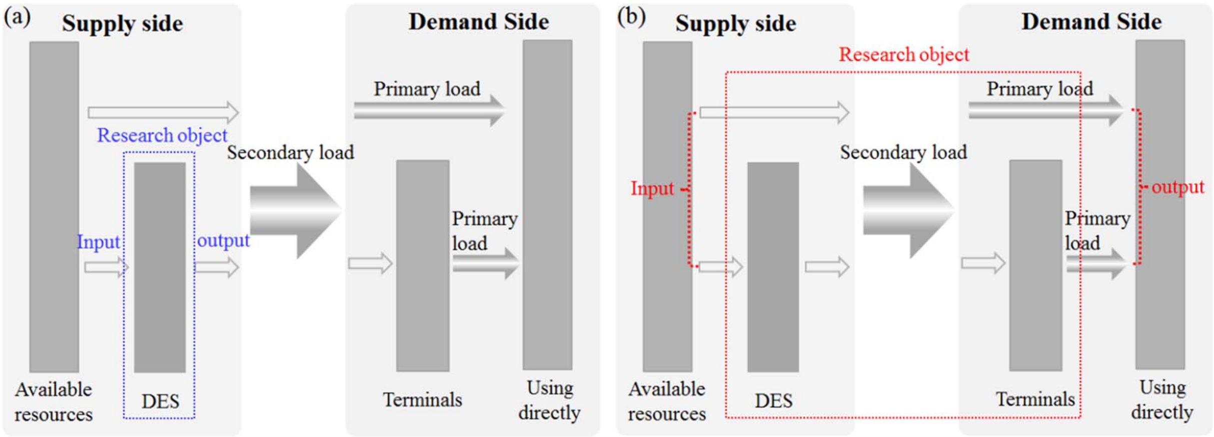


Fig. 3. The evaluation system. (a) The traditional evaluation system. (b) The evaluation system of the whole district.

characteristics from Refs. [10–14,29–31].

For an expansion scheme, the real-time value and total amount of energy supply and demand should maintain balance. The energy balance equations are listed below:

$$E_{eg\to e} + E_{CHP\to e} + E_{DCHP\to e} + E_{re\to e} = D_e + E_{e\to hp} + E_{e\to wc} + E_{e\to EAC} \tag{2-1}$$

$$E_{hn\to h} + E_{CHP\to h} + E_{DCHP\to h} + E_{hp\to h} + E_{b\to h} + E_{re\to h} + E_{es\to h} = D_h + E_{h\to es} + E_{h\to LARU} \tag{2-2}$$

$$E_{DCHP\to c} + E_{hp\to c} + E_{wc\to c} + E_{es\to c} = D_c + E_{c\to es} \tag{2-3}$$

$$E_{sf\to f} = D_f + E_{f\to CHP} + E_{f\to DCHP} + E_{f\to b} \tag{2-4}$$

The arrow in the subscript represents the flow of energy, with the letter at the starting point referring to the input energy or equipment which provides energy and the letter at the ending point referring to the output energy or equipment that consumes energy.

In addition, in order to guarantee normal operation, the actually instantaneous output of any equipment should be within the range shown as Eq. (2-5). Generally speaking, the maximum output is equal to the rated one. In terms of gas internal combustion engines (GICEs), the minimum output is 50% of the rated one, since the efficiency is on a low level when the actual output is equal to or lower than 50% of the rated output capacity.

$$E_{min} \leqslant E \leqslant E_{max} \tag{2-5}$$

Different from newly-built area, the expansion planning of existing DESs is based on the original one, which results in a limited number of independent variables. Therefore, in this paper, the optimum expansion scheme is selected by evaluating and comparing several schemes according to an evaluation system after multiple expansion schemes are determined.

2.4.2. Evaluation system of the whole district

As shown in Fig. 3(a), the traditional evaluation method of DES takes DES itself as the research object. For example, energy usage efficiency is the ratio of energy output to input of the DES. Another example is that CO_2 emission refers to the amount of CO_2 emitted by the DES and in the production process of input energy. The traditional evaluation method can evaluate energy usage and environment impact of the DES, but does not consider two aspects: (1) the part of available resource directly flowing to the demand side; (2) energy usage of terminals on demand side. Consequently, the traditional evaluation method is only suitable for the situation where the planning of DES has no impact on the two aspects mentioned above. However, in the expansion planning of existing DESs, different expansion schemes usually have different impacts on the two above-mentioned aspects when terminal replacement is implemented on demand side to improve secondary load structure. Therefore, a good evaluation system which is used to compare and select the optimum expansion scheme should take into full account the impact of a specific expansion scheme on the whole district, i.e., it should include aspect (1) and (2). In this regard, this section comes up with the evaluation system of the whole district. As shown in Fig. 3(b), the research object of the new evaluation system is the energy conversion system of the whole area, including DES on supply side and terminals on demand side, and the input and output are available resources and primary load, respectively. Input energy, input exergy, CO_2 emission, and total investment are used as evaluation indicators in this new evaluation system, which reflects the performances of different schemes in three aspects: energy efficiency, environmental friendliness and economy.

(1) Analysis of energy and exergy

The analysis of energy is based on the conservation of the quantity of energy and reveals the conversion, transference and loss of energy quantity. The energy conversion efficiency is presented as Eq. (2-6), where Q_j represents different types of output energy and W_i represents different types of input energy.

$$\eta = \frac{\sum_{j=1}^{n} (Q_j)}{\sum_{i=1}^{n} (W_i)} \tag{2-6}$$

The analysis of exergy is based on the first law and second law of thermodynamics to reveal the conversion, transference and loss of energy quality. The exergy conversion efficiency is presented as Eq. (2-7), where λ refers to the energy quality coefficient of different types of energy. The larger it is, the larger the proportion of exergy will be.

$$ECC = \frac{\sum_{j=1}^{n} (Q_j \times \lambda_j)}{\sum_{i=1}^{n} (W_i \times \lambda_i)} \tag{2-7}$$

The definition of the energy quality coefficient is presented as Eq. (2-8), where EX_i represents the amount of energy which can be converted into work in a certain type of energy and E_i represents the amount of the certain type of energy.

$$\lambda_i = \frac{EX_i}{E_i} \tag{2-8}$$

The equations of the energy quality coefficients of different types of energy [32] are listed in Table 3.

In the expansion planning of DES, since the primary load of the energy supply side is fixed, the output energy and output exergy of the system stay the same even though the plans are different. In view of this, input energy W_E and input exergy W_{EX} are selected to be the

Table 3
Calculation equations of energy quality coefficients.

Type	Equations	Type	Equations	Type	Equations
Cool water	$\lambda_{cw} = \frac{T_0}{T_s - T_r} ln\frac{T_s}{T_r} - 1$	Cooling	$\lambda_c = \frac{T_0}{T_{cd}} - 1$	Electricity	$\lambda_e = 1$
Hot water	$\lambda_{hw} = 1 - \frac{T_0}{T_s - T_r} ln\frac{T_s}{T_r}$	Heating	$\lambda_h = \frac{T_0}{T_{hd}} - 1$	Steam	$\lambda_{st} = 1 - \frac{T_0}{T_{st}}$
Fossil fuel	$\lambda_f = \eta_f(1 - \frac{T_0}{T_{burn} - T_0} ln\frac{T_{burn}}{T_0})$				

evaluation indicators.

$$W_E = \sum_{i=1}^{n} (W_i) \tag{2-9}$$

$$W_{EX} = \sum_{i=1}^{n} (W_i \times \lambda_i) \tag{2-10}$$

(2) CO_2 emission

The CO_2 emission of a system is mainly generated in three ways: (1) direct emission due to fuel combustion within the system, (2) indirect emission of purchased secondary energy resources and (3) indirect emission of equipment and ducts of a system. Only direct emission and indirect emission of purchased secondary energy resources are considered in this method. The emission of CO_2 can be calculated according to Eq. (2-11), where *MCO2*, *Ei,* and Ef_i refer to the emission of CO_2, the amount of the input energy and the CO_2 emission coefficient, respectively.

$$M_{CO_2} = \sum_{i=1}^{n} E_i \times Ef_i \tag{2-11}$$

The CO_2 emission coefficient Ef_i presents the CO_2 emission per unit of production *i*.

(3) Total investment

When taking the energy conversion system of the whole district as the evaluation object, the total investment is aimed at expanding energy supply capacity of DESs and achieving the goal of energy saving and reduction of CO_2 emission within the whole district. The investment scope of expansion planning includes the equipment and techniques used in DES on supply side, energy efficiency measures and terminals replacement on demand side.

Different from the traditional evaluation system which calculates the investment and payback period from the perspective DESs investor, the new evaluation system takes the whole district into account and thus does not evaluate expansion schemes from the interest of any stakeholder such as the DES investor or the occupant. Therefore, payback period is not involved here.

3. Case study

3.1. Case overview

Ningbo Hi-Tech District, China, is a mixed community which covers an area of 18.9 square kilometers (see Fig. 4). The existing KF plant provides steam to the community as the DES, and also exports steam to District A and District B which are adjacent to Hi-Tech District. The year when the expansion planning was made is defined as the base year 2013. According to the local planning commission, the floor area of Hi-Tech District and District A will increase drastically in the next three years (from 2014 to 2016), and the industrial output in Hi-Tech District will grow at the total rate of 40%, which will lead to the steam demand of Hi-Tech District and District A increasing rapidly while that of District B remains nearly unchanged in three years. Additionally, as can be seen from the operating data of KF plant, the average operational efficiency fluctuated between 45.4% and 51.7%.

In order to improve the existing DES, the methodology in Section 2

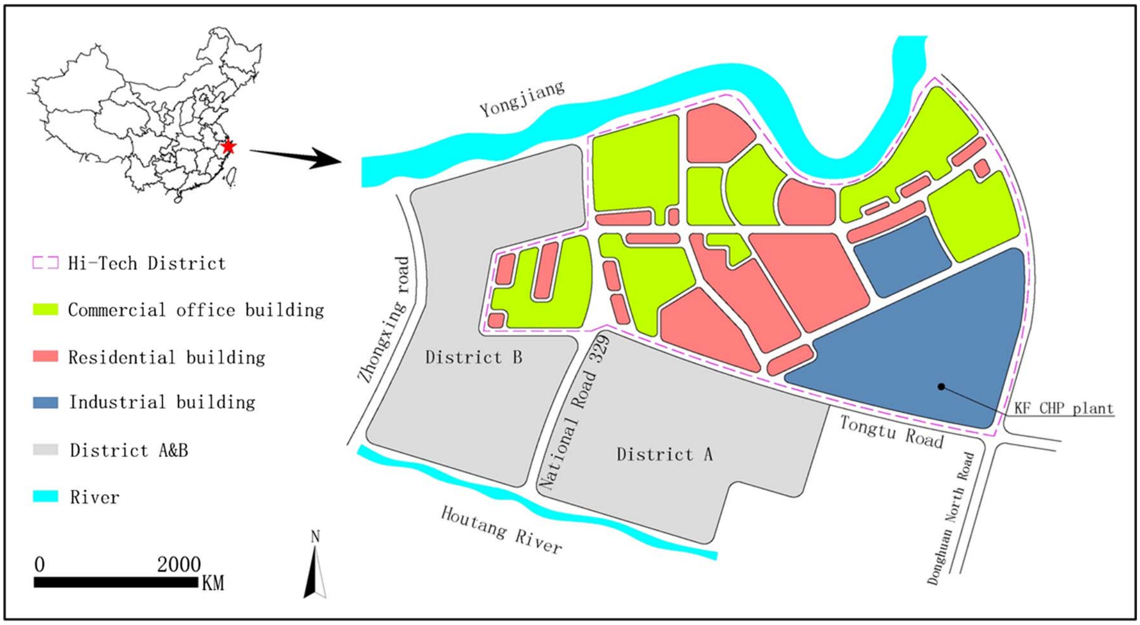


Fig. 4. The map of the planning area in Ningbo city, China.

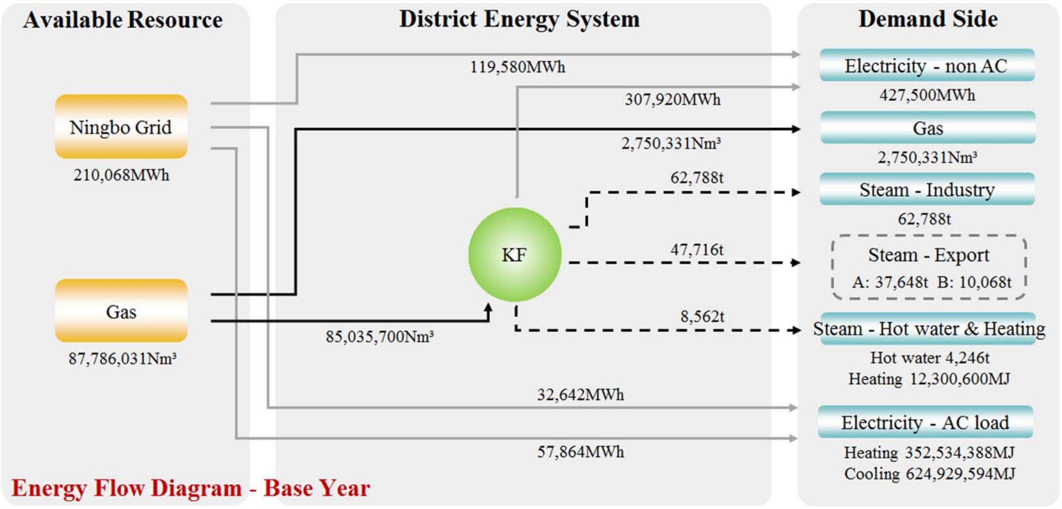


Fig. 5. Energy flow diagram in the base year.

is applied in the expansion planning of DES in Hi-tech District, which includes four aspects: the problem analysis of the existing DES, demand analysis, available energy resource assessment and expansion of the existing DES.

3.2. Base year status and problem analysis

3.2.1. Energy supply and demand situation

As shown in Fig. 5, KF plant provides steam to Hi-Tech District for the use of light industry, domestic hot water and the heating of some commercial office buildings. And meanwhile, KF plant exports steam to Districts A and B for domestic hot water and heating in some of the commercial office buildings. Heating load of other commercial office buildings as well as buildings of all other types and all cooling load in this area are supported by EACs. In terms of electricity and gas, the electricity generated by KF plant is integrated into the national grid, and the electricity and gas demand on demand side are supplied by the national grid and gas network.

In Fig. 5, the energy consumption of electricity, steam and gas are obtained by referring to the energy consumption monitoring systems of power plant, gas supplying company and terminal users. Cooling and heating load density e_k of buildings of type k are modeled with EnergyPlus, a commonly used building simulator, and calibrated with practical electricity consumption. Then the total cooling or heating load can be gained according to Eq. (3-1), where S_k refers to the floor area of buildings of type k.

$$E = \sum_{k}^{N} e_k S_k \tag{3-1}$$

3.2.2. Configuration and operation status of KF plant

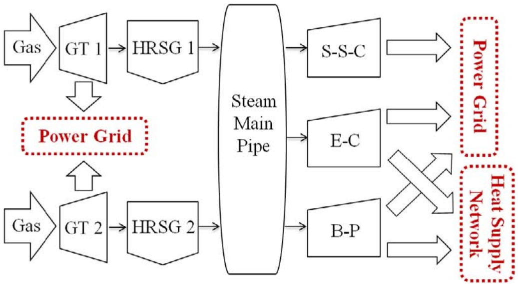
The existing DES of Hi-Tech District, i.e., the KF plant, consists of gas-steam CHP units with the configuration information shown in Fig. 6 and two gas boilers with a rated steam supply capacity of 20 tons/h and efficiency of 90.7%. KF Plant can achieve a maximum heat supply capacity of 137 tons/h, including 97 tons/h from the CHP units and 40 tons/h from gas boilers.

According to the operating data provided by KF plant, in winter, the steam supply flow rate of the plant is between 40 and 60 tons/h in 80% of the working time. In the rest of the time, the steam supply flow rate is about 100 tons/h or 20 tons/h. The maximum instant flow rate in winter can be up to 112.6 tons/h. In spring, summer and autumn, the steam supply flow rate of the plant is around 16 ton/h during half of the working time. The maximum instant flow rate in these three seasons is only about 70.1tons/h. In the base year, the efficiency of KF's CHP units fluctuated between 45.4% and 51.7%, and averaged at 48.1%, which is lower than the national requirement of 55%.

As can be seen from the above data, the steam output of KF plant is relatively low compared with the installed capacity of CHP units. In addition, the part of steam for heating is only needed in winter, which results in a seasonal difference of steam demand and the lower steam output of KF plant in spring, summer and autumn. Low steam demand and large seasonal difference of steam demand are the main reasons for the low efficiency of CHP units. Because the operational efficiency of CHP units is closely related to the steam output, the ratio of heat output should be increased while that of electricity generation should be reduced in order to improve the overall efficiency of CHP units in the expansion planning. Moreover, increasing the steam supply will also reduce the loss rate of steam in the pipe network.

3.2.3. Demand growth

According to the local planning commission, the floor area of commercial office building in Hi-Tech District and District A and the industrial output increase with the total rate of 33%, 28% and 40%



Description	E-C	B-P	E-C & B-P
Steam production, ton/h	40	57	97
Power generation, MW	54.62	43.62	78.22
Gas consumption, Nm³/h	12,500	12,500	25,000
Generator unit efficiency	69.0%	71.0%	62.0%
Heat electricity ratio	0.580	1.03	0.98

Fig. 6. Flowchart of gas-steam combined cycle generator units and theoretical efficiency.

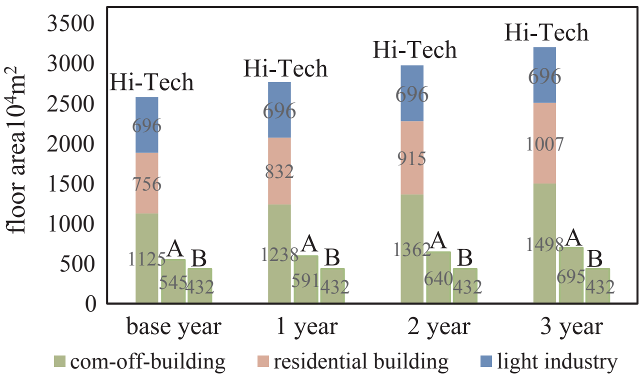


Fig. 7. Changes of floor area within 3 years.

respectively over the next three years. The growth of floor area in Hi-Tech District, District A and District B is shown in Fig. 7.

The operating data of KF Plant shows that KF Plant has heat supply surplus 24.4tons/h in winter and 69.9tons/h in summer when instant flow rate of steam demand reach its maximum values. It cannot be determined that whether the current heat supply surplus of KF plant can satisfy the steam demand increase caused by the floor area and industrial development.

3.2.4. Problem summary

It is obvious from the previous analysis that there are two major problems in DES of the base year. For the first, low steam demand and the large seasonal difference of the steam demand result in low operational efficiency of CHP units in KF plant. Moreover, the floor area of Hi-Tech District and District A and industrial output in Hi-Tech District will increase drastically in the next three years, which makes it possible that the steam demand in three years will exceed the steam supply capacity of KF plant.

3.3. Demand analysis of assigned area

As for the energy demand forecast, supposing building primary load density and energy consumption per unit of industrial product stay on the same level in three years, we can calculate each type of primary load E_i by area expansion and output expansion presented as Eq. (3-2), where $E_{i,ind}$ and $e_{i,k}$ refer to industrial load and load densities in buildings of type k in the base year and γ and S_k refer to the total increase rate of production and total floor area of buildings of type k in three years.

$$E_i = E_{i,ind}\cdot(1+\gamma)+\sum_{k}^{N} e_{i,k}S_k \tag{3-2}$$

Considering the convenient management and project implementation, the energy saving measures of the demand side are primarily implemented in commercial office buildings in Hi-Tech District. Based on the operating conditions in the base year, four energy conservation recommendations are proposed in Table 4. Then, EnergyPlus is used to simulate energy saving performance of those energy saving measures on a commercial office building $\varepsilon_{i,co}$, with the result extended to all commercial buildings. The calculation equation of each type of primary load after considering energy saving measures E_i' is shown as Eq. (3-3), where S_{co-HT} refers to the total floor area of commercial office buildings in Hi-Tech District. The comprehensive energy saving rate of these four energy saving measures can amount to 13%.

$$E_i' = E_i - \varepsilon_{i,co}S_{co-HT} \tag{3-3}$$

Besides, to increase the steam demand in summer, LARUs are advocated to improve the secondary load structure. Considering that consumers tend to use electrical equipment for cooling, we suppose that approximately 10% and 25% of new building floor area of Hi-Tech District and District A adopt LARUs to supply hot or cool water, and the floor area which adopts steam heating in three years stays the same as that in the base year. There exist two means to adopt LBAUs. When units are installed on demand side, they work as terminals, and the secondary load is steam. When installed on supply side, LARUs work as part of the DES, providing AHUs with hot or cool water, and the secondary load is hot or cool water. Load structures in the base year and the two options above are illustrated in Fig. 8.

Since nominal conservation efficiency of all types of terminals are known, the calculation formula of each type of secondary load D_j is presented as Eq. (3-4), where $\eta_{i-j,k}$ and $\eta_{i-j,co-HT}$ refer to energy

Table 4
Energy conservation recommendations for commercial office buildings.

Type	Base year status	Recommendations
1. Lighting system	LED, but without smart control	LED lights with daylighting control
2. Sunshade facilities	Concave windows; rely on the building structure to provide shading	Horizontal sunshade to be added on the southern facade and vertical sunshade to be added on the western facade
3. Refrigeration unit	The COP of VRV units is less than 3	Increase the COP of VRV units to 3.5
4. Transmission and distribution system	Pumps in the AC system are mostly fixed flow rate pumps	Replace the pumps with variable flow rate pumps

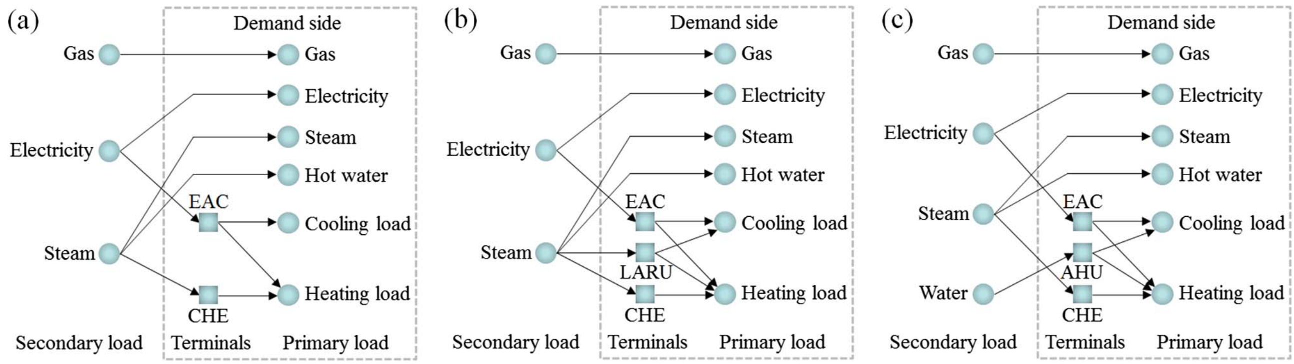


Fig. 8. Load constructions. In base year (b) Option I in 3 years (c) Option II in 3 years.

Table 5
Results of secondary load forecasting.

Primary load	Secondary load	Option I		Option II		Option III	
		Hi-Tech	Export	Hi-Tech	Export	Hi-Tech	Export
Electricity	Electricity, MWh	616,114	–	616,114	–	625,568	–
Gas	Gas, Nm^3	5,245,350	–	5,245,350	–	5,245,350	–
Steam	Steam, ton	87,903	–	87,903	–	87,903	–
Hot water	Steam, ton	4246	23,900	4246	23,900	4246	23,900
Cooling load	1. Electricity (EAC), MWh	72,408	–	72,408	–	84,700	1809
	2. Steam (LARU), ton	14,113	8282	–	–	–	–
	3. CW (AHU), MJ	–	–	38,210,948	22,423,515	–	–
Heating load	1. Steam (CHE), ton	4316	23,816	4316	23,816	4316	23,816
	2. Electricity (EAC), MWh	42,492	–	42,492	–	49,447	1021
	3. Steam (LARU), ton	7210	4231	–	–	–	–
	4. HW (AHU), MJ	–	–	19,521,075	11,455,433	–	–

conservation efficiency from secondary load j to primary load i in buildings of type k and commercial office buildings. The COP of EACs and LARUs are set at 3.5 and 0.95, and the steam heat value is 2850 MJ/ton. The calculation results of the two options in three years are presented in Table 5.

$$D_j = E_{j,ind}\cdot(1+\gamma) + \sum_{K}^{N}\sum_{i}^{n}(e_{i,k}S_k/\eta_{i-j,k}) - \sum_{i}^{n}(\varepsilon_{i,co}S_{co-HT}/\eta_{i-j,co-HT}) \tag{3-4}$$

In order to analyze the energy-saving effect of the above measures for energy conservation and secondary load structure improvement, Option III are designed to act as the benchmark. In Option III , energy conservation and secondary load structure improvement are not implemented and heating and cooling load of new buildings in Hi-Tech District and District A are all supported by EACs. The calculation results of the Option III in three years are presented in Table 5.

3.4. Renewable energy utilization in Hi-Tech District

Ningbo enjoys rich natural conditions for the utilization of wind energy, solar energy, geothermal energy and tidal energy. Since Hi-Tech District is not geographically located in a coastal area, the utilization of tidal energy is thus unrealistic. Besides, a large number of buildings have been built in this district so that little ground space can be used for ground source heat pumps. Data provided by the Hi-Tech District Administrative Committee show that the industrial buildings suitable and recommended for solar panels have a total roof area of 350,000 m^2, which allows for an installed capacity of approximately 35 MW according to Ref. [33]. Therefore, the project will primarily consider the possibility of adding rooftop solar PV systems on existing industrial buildings. The calculation process and results are shown in Table 6.

Table 6
Solar power generation in Hi-Tech District.

Description	Value
Total installed area, m^2	350,000
Total installed capacity, MW, W	35
Annual radiation on horizontal plane, MJ/m^2, Ra	4700
Annual peak sunshine hours, h, H[a]	1302
Operational efficiency of PV system, η_s	0.757
First year annual power generation, MWh, L_0[b]	34,508
Annual attenuation rate	0.8
Service life, year	20

Note:
[a] 1 MJ/m^2 = 23.889 cal/cm^2. When radiation is measured against cal/cm^2, $H = Ra \times 0.0116$ (conversion factor).
[b] $L_0 = W \times H \times \eta_s$.

3.5. Expansion schemes of the DES in Hi-Tech District

We can see from the data in Table 5 that after the terminals replacement on demand side, three options have different secondary load structures. This part will present three expansion schemes based on the three options introduced in Section 3.3 respectively. Both Option I and Option II adopt solar PV systems to supply electricity. Option III , as the benchmark, does not adopt solar PV systems.

3.5.1. Option I: Capacity expansion of KF plant

In Option I, LARUs are installed on demand side, as already mentioned, and they work as terminals. On supply side, two gas boilers are added to KF plant to satisfy the steam demand in three years in Option I. The steam supply and demand are analyzed for two scenarios separately and the calculation process is illustrated in Table 7. The detailed planning of Option I is presented in the following:

(1) Configuration: adding two 15 ton/h gas boilers to the original configuration of KF plant; solar PV systems with a total capacity of 35 MW.
(2) Mode of operation: to address the growth of steam demand, gas-steam CHP units will first be utilized following the principle of using the backpressure turbine first and then the extracting-condensing turbine.

Following energy balance equations are used to calculate the energy flow of Option I in Hi-Tech District through the third year and calculation results are depicted in Fig. 9, which aim to reflect the conversion, flow and utilization of electricity, gas and steam.

$$E_{eg\to e} + E_{KF\to e} + E_{re\to e} = D_e \tag{3-5}$$

$$E_{KF\to h} = D_h \tag{3-6}$$

$$E_{sf\to f} = D_f + E_{f\to KF} \tag{3-7}$$

3.5.2. Option II: Capacity expansion of KF plant+ DCHP units

Option II introduces GICEs, which are combined with LARUs to configure DCHP units on supply side. Moreover, gas boilers are added to existing KF plants to expand the capacity.

Because LARUs supply cool or hot water for air conditioning, the part of steam for LARUs fluctuates a lot with seasonal change and is needed for a short period. Furthermore, approximately 12% of the total steam demand is consumed by LARUs to supply the AHUs. Therefore, GICEs are introduced in Option II to supply part of the steam for LARUs to alleviate its detrimental effect on KF plants.

Considering that the GICE will operate poorly when its load is less than 50% of the rated capacity, the capacity of GICEs is set at 20% of the peak value of the total steam consumption of LARUs. When the need for steam exceeds the capacity of a GICE or is smaller than 50%, the

Table 7
Steam supply requirement of KF plant in three years in three options.

Description	Option I		Option II		Option III	
	Winter	Spring–Autumn	Winter	Spring–Autumn	Winter	Spring–Autumn
Total steam demand, ton	70,119	107,898	63,603	98,137	52,851	91,330
Average demand flow rate[a], ton/h	80.1	41.3	72.7	37.4	60.4	34.8
Max demand flow rate, ton/h, D_M	135.2	70.4	123.6	63.6	102.0	59.3
Pipeline loss, %, u	19.4%	32.8%	19.4%	32.8%	19.4%	32.8%
Maximum supply flow rate, ton/h, S_M[b]	167.7	104.8	153.3	94.6	126.6	88.3
Heat supply capacity of existing KF plant, ton/h, C	137	137	137	137	137	137
Heat supply gap, ton/h, G[c]	30.7	None	16.3	None	None	None
Gas boilers selection	15 ton/h * 2	15 ton/h * 2	10 ton/h * 2	10 ton/h * 2	–	–
Steam supply capacity of KF after expansion, t	167	167	157	157	–	–
Electricity, MWh	96,462	137,095	86,312	121,095	108,746	262,851
Gas consumption, Nm^3	26,107,919	34,523,872	23,784,505	30,497,386	30,383,670	69,226,263

Note:
[a] The unit works 875 h in winter and 2625 h during other times.
[b] $S_M = D_M/1{-}u$.
[c] $G = S_M{-}C$.

excessive part of steam or all the need for steam will be provided by the steam network of KF plant. For KF plant, its capacity is expanded by setting additional gas boilers because the surplus is not able to fulfill the increasing need for industry steam and the insufficient part of GICEs.

The detailed planning of Option II is presented in the following according to the analysis above.

Configuration:

(1) Hi-Tech District adopts three GICEs and District A adopts two GICEs, with a rated capacity of each machine of 2 MW, the rated electricity generation efficiency of 44% and the rated heating efficiency of 40%. The calculation results are listed in Table 8.
(2) Two 10 ton/h gas boilers are added to KF plant. The process of calculation and analysis are presented in Table 7.
(3) Solar PV systems of 35 MW are installed on the rooftops of existing buildings.

Mode of operation:

(1) When the steam demand of LARUs is less than the capacity of a single GICE and exceeds 50% of E^{Ca}, the steam will be supplied by GICEs. Otherwise, the steam will be supplied by the steam network of the KF plant.
(2) The mode of operation of gas-steam CHP units is the same as that of Option I.

Table 8
Full year operational data of DCHP units.

Description	DCHP units in Hi-Tech District	DCHP units in District A
Cooling capacity of supplying cold water, MJ	38,210,948	22,423,515
Heating capacity of supplying hot water, MJ	19,521,075	11,455,433
Full year electricity generation, KWh	7,795,000	5,055,000
Full year gas consumption, Nm^3	1,808,000	1,172,000

Following energy balance equations are used to calculate the energy flow of Option II in Hi-Tech District through the third year and calculation results are depicted in Fig. 10, which reflects the conversion, flow and utilization of electricity, gas steam, hot water and cold water.

$$E_{eg\to e} + E_{KF\to e} + E_{DCHP(Hi-Tech)\to e} + E_{DCHP(A)\to e} + E_{re\to e} = D_e \tag{3-8}$$

$$E_{KF\to h} = D_h + E_{h\to DCHP(A)} + E_{h\to DCHP(High-tech)} \tag{3-9}$$

$$E_{eg\to e} + E_{KF\to e} + E_{DCHP(Hi-Tech)\to e} + E_{DCHP(A)\to e} + E_{re\to e} = D_e \tag{3-8}$$

$$E_{KF\to h} = D_h + E_{h\to DCHP(A)} + E_{h\to DCHP(Hi-Tech)} \tag{3-9}$$

$$E_{DCHP(Hi-Tech)\to c} + E_{DCHP(A)\to c} = D_c \tag{3-10}$$

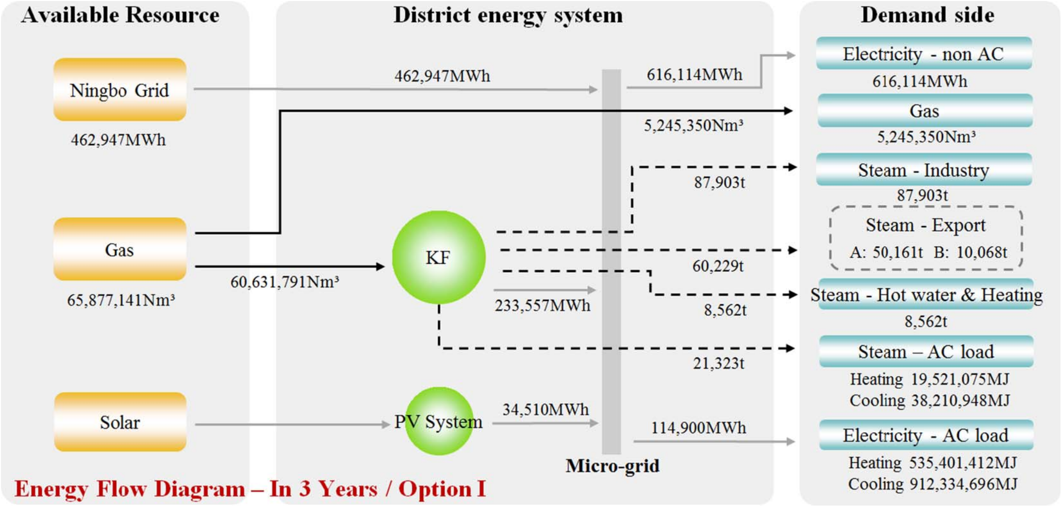


Fig. 9. Energy flow diagram of Option I in three years.

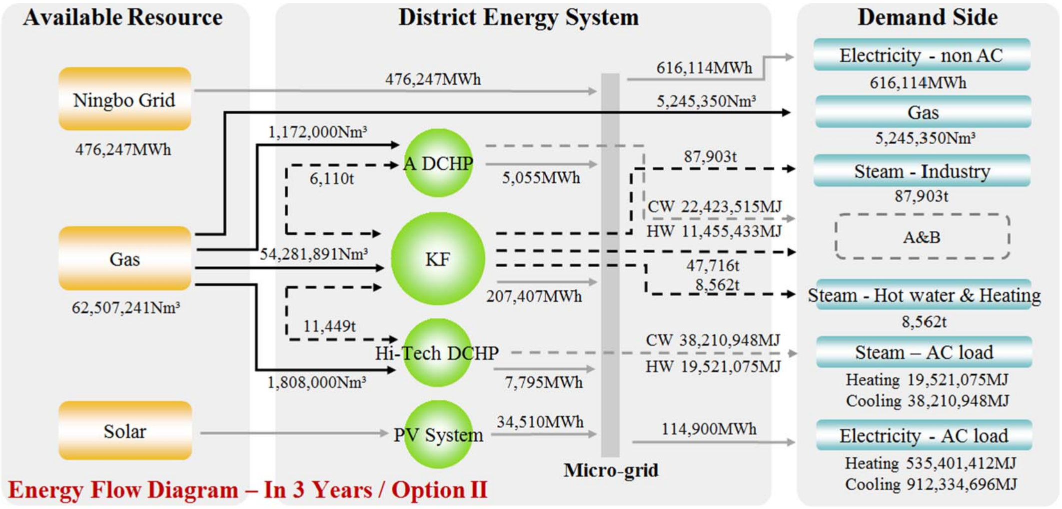


Fig. 10. Energy flow diagram of Option II in three years.

$$E_{sf\to f} = D_f + E_{f\to KF} + E_{f\to DCHP(Hi-Tech)} + E_{f\to DCHP(A)} \tag{3-11}$$

3.5.3. Option III: No expansion of KF plant

For Option III , the steam supply and demand are analyzed for two scenarios separately and the calculation is illustrated in Table 7. It can be seen from the calculation results that current KF plant can satisfy the steam demand in three years under the circumstance that heating and cooling load of new buildings in Hi-Tech District and District A are all supported by EACs. Therefore, Option III does not expand the current KF plant.

3.5.4. Evaluation of expansion schemes

The three options above are different not only in the configuration mode of DES but also in the terminals on demand side. We will then evaluate these three options with the evaluation system of the whole district. The research object is DES on supply side and all terminals on demand side, namely:

- Expanded KF plant, solar PV systems and the terminals including air-conditioners, LARUs, CHE, etc. in Option I.
- Expanded KF plant, solar PV systems, DCHP units in Hi-Tech District and District A, and terminals including air-conditioners, AHUs, CHE, etc. in Option II.
- Existing KF plant and terminals including air-conditioners, etc. in Option III.

The major calculation parameters used for the calculation of evaluation indicators are presented in Table 9 according to the investigation and research of local conditions. The calculation results of evaluation indicators of three options are presented in Table 10.

Table 9
The main parameters of the evaluation system.

Description	Symbol	Value
Reference temperature in spring, summer and autumn, K	$T_{0,ssa}$	301.45
Reference temperature in winter, K	$T_{0,win}$	278.15
Theoretical combustion temperature of natural gas, K	T_{gas}	1573.15
Average conversion efficiency of natural gas	η_f	0.8
CO_2 emission coefficient of national grid, kg CO_2/MWh	Ef_{eg}	810.0
CO_2 emission coefficient of natural gas, kg CO_2/Nm^3	Ef_{gas}	2.09
Gas heat value, kcal/Nm^3		8400

Note: The local daily average temperature in winter is taken as $T_{0,win}$. The local daily average temperature in summer is taken as $T_{0,ssa}$.

Table 10
Evaluation results of three options by the new evaluation system.

Description	Option I	Option II	Option III
Electricity consumption, MWh	462,947	476,247	406,948
Gas consumption, Nm^3	65,877,141	62,507,241	104,855,283
Input energy, MJ	3,982,924,578	3,912,315,052	5,151,844,085
Input exergy, MJ	2,815,895,401	2,804,984,453	3,294,307,879
CO_2 emission, ton	512,670	516,400	548,775
Investment, USD	50,852,224	63,491,763	0

Data in Table 10 shows that the input energy, input exergy and CO_2 emission are reduced by 22.7%, 14.5% and 6.6% respectively in Option I, and 24.1%, 14.9% and 5.9% respectively in Option II. The effects of energy-saving, exergy-saving and CO_2 emission reduction caused by energy conservation and secondary load structure improvement are 20.3%, 10.8% and 1.5% respectively in Option I, and 21.6%, 11.1% and 0.8% respectively in Option II. It is obvious that significant energy-saving effect and CO_2 emission reduction benefits of the whole district are achieved through the implementation of energy-saving renovation on demand side, secondary load structure improvement, solar energy utilization and efficient technologies such as DCHP on supply side. In order to satisfy the energy demand growth in the future and realize energy conservation and emission reduction, the investment of Option I and Option II are 50,852,224 and 63,491,763 dollars respectively. Additionally, 44,580,747 dollars out of the total investment is spent on the installation of the solar PV system. We can learn from the comparison of Option I and Option II that Option I performs better in terms of CO_2 emission reduction and Option II in energy conservation. Besides, Option II costs more than Option I due to the application of DCHP units on supply side. Consequently, Option II is obviously not the optimum option in terms of two aspects: (1) energy conservation and CO_2 emission reduction; (2) economy. However, when the traditional evaluation system is applied, the evaluation will draw a contrary conclusion side as shown in Table 11. When the traditional evaluation system is applied, only DES, namely KF plant and the solar PV system are considered in Option I, and KF plant, the solar PV system and DCHP units in Option II. Table 11 shows that Option II performs better than Option I on both energy conservation and CO_2 emission reduction. These effects are even more obvious than that as shown in Table 10. This result indicates that despite less energy consumption and CO_2 emission of the DES, energy consumption and CO_2 emission of

Table 11
Evaluation results of two options by the traditional evaluation system.

Description	Option I	Option II
Electricity input, MWh	233,557	207,407
Gas input, Nm^3	60,631,791	54,281,891
Input energy, MJ	2,972,688,092	2,655,278,369
Input exergy, MJ	1,898,581,534	1,693,661,796
CO_2 emission, ton	315,902	281,449
Investment, USD	45,029,546	62,981,524
Payback period, year	6.99	8.12

terminals on demand side in Option II are higher than that in Option I. In terms of investment, since the cost of the LARUs used on demand side is not considered in Option I, the investment of Option I is further lower than that of Option II. From the perspective of the interest of the DES investor, payback periods of DES in Option I and Option II are shown in Table 11 with sales revenues, energy consumption, government subsidies, maintenance cost, employee salaries and space rental considered. Consequently, the traditional evaluation system can only evaluate the DES and the interest of the DES investor in expansion planning, rather than the impact of expansion schemes on the whole district.

4. Conclusions

In order to address the issues of low system efficiency and peak-time energy supply deficiency in some existing DESs, a systematic methodology for expansion planning of existing DESs is proposed in this paper. Besides, expansion planning of the existing DES in Ningbo Hi-Tech District, China, as a case study, illustrates the application of the methodology for expansion planning of existing DESs.

This expansion method includes four parts: problem analysis in current DES, demand side analysis, available energy resource assessment and the existing DES expansion. The utilization of demand side resource, renewable energy and high efficient technologies is emphasized. In demand side analysis, prediction of energy demand increase, the energy-saving transformation and amelioration of secondary load properties are included. The new concept of secondary load structure, an important load property, and its improvement method are put forward. In the part of existing DES expansion, the evaluation system of the whole district, which takes DES on supply side and all terminals on demand side as the research object, is adopted for comparison and selection of multiple schemes to reflect the impact of expansion schemes on the whole district. In the case study, expansion results demonstrate that input energy, input exergy and CO_2 emission are reduced by 22.7–24.1%, 14.5–14.9% and 5.9–6.6% respectively due to the energy-saving renovation on demand side, secondary load structure improvement, utilization of solar energy and efficient technologies on supply side. The effects of energy-saving, exergy-saving and CO_2 emission reduction through demand side management are 20.3–21.6%, 10.8–11.1% and 0.8–1.5% respectively. The comparison of evaluation results by the traditional and the new evaluation system reveals that the new evaluation system which takes all energy conversion systems in a district as the research object performs better in reflecting the impact of an expansion scheme on the whole district, and thus should be a preferred choice. Also, we can use the new and the traditional system together to evaluate expansion schemes from different perspectives, which means using the new evaluation system to evaluate impact of an expansion scheme on the whole district and using the traditional system to evaluate the interest of DES investor when adopting a certain scheme.

The methodology proposed in this paper is appropriate for existing DESs when the energy supply capacity and operational efficiency need to be increased. Secondary load structure improvement and the new evaluation system of the whole district in this paper can also offer reference or be used under other circumstances where energy forms on supply and demand side do not match with each other, or several schemes are needed to be compared. However, it should be noted that the optimum expansion scheme is selected by evaluating and comparing several schemes in this paper, which makes the expansion planning time-consuming. Therefore, further research is needed to find out quicker approaches to obtain the optimum scheme such as using optimization algorithm to obtain the optimum expansion scheme with constraints from the original system configuration taken into account.

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