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Integrated Urban Energy Planning: A Case-Study Using Optimization

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Abstract. This article describes an integrated energy planning optimization case-study. Starting from an integrated urban energy planning practice based on the urban planning information, an optimization approach is implemented to support decisions on suitable energy structures. Based on a use-case, energy demand, renewable energy resources, energy policy and energy prices are analyzed and set as inputs of the optimization. The results are energy structures minimizing the cost for two separated zones. Meanwhile, under different scenarios, in terms of renewable ratio targets and thermal storage, comparison is made for illustrating economy differences. The optimization mentioned in the article is modelled as a *Mixed-Integer Linear Programming* problem, which can search the optimal solution with high efficiency among the possible system designs.

Keywords: Integrated energy planning, optimization, renewable

1. Background

In China, traditional urban energy planning usually exists as several separated special energy planning (e.g., gas. electricity, heating) which are made by different institutes [1]. Consequences caused by these separated energy plannings are repetitive load prediction, oversized energy equipment, superfluous investment and inefficient energy operation [2]. Meanwhile, these "energy supply" oriented plans rarely consider energy structure, energy utilization mode, energy efficiency indicators as well as related environmental targets.

In recent years, increasingly urban green and low-carbon development popularizes distributed renewable, district energy, thermal storage, and local multi-energy system in the city. Integrated urban energy planning is emerging to better integrate all these energy aspects as a whole and efficient system. However, the diversity of energy demand, energy resources, technologies as well as local policies, increases complexity in the urban energy planning, which needs optimization tools to help find the best energy solution for cities.

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2. Introduction of optimization tools

The tool discussed in this paper is an optimization software for sizing a multi-energy system at district scale. It is developed under a *Mixed-Integer Linear Programming* framework to search an optimal energy solution, maximizing economy under various environmental and technical constraints in the city.

Inputs of the tool are the urban energy demand (electricity, heating, cooling) estimated based on the urban design, available potential of local renewable resources, energy tariff and related policies, as well as energy equipment information including efficiency, investment, maintenance cost, and service life.

Based on the annual estimated energy demand, we select several typical days and extreme days to represent the total demand and the extreme demand in a year. Local renewable potential will give the limitation when sizing an energy system. Energy tariff and equipment cost of each energy technology are part of the objective function.

The output of the tool is an optimal multi-energy solution including the choice of energy technologies, the installed capacities, and the phasing scheme for a multi-phase deployment.

3. Case study

A use-case is made in a real city zone, demonstrating the approach in an integrated energy planning project.

a. Introduction of the Zone

The use-case is located in a new urban area of a city in the middle of China, the optimization is applied during the urban design phase. The study zone covers an area of 1.85 km^2, it is a multi-functions zone, and total floor area is 890,000m^2, figure 1 shows the land function of the study zone.

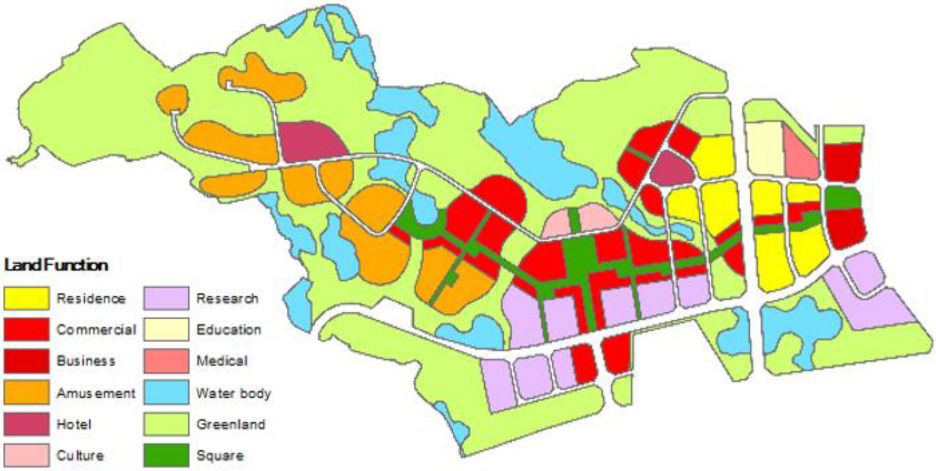

Figure 1. Land function of the study zone.

b. Pre-study of Energy Condition

Based on land functions and floor area, a simulation is conducted to estimate energy demands (heating, cooling and electricity). By considering local climate, building types, envelope structure, operation mode, the annual hourly demand is estimated, which is one of the main input data for the optimization. The annual accumulated energy demand is then distributed to each plot, show in figure 2. The spatial distribution and the density of the energy demand provide valuable indications for positioning the energy systems.

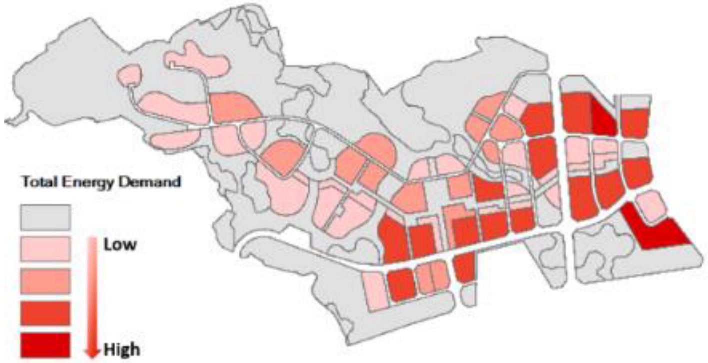

Figure 2. Energy demand distribution.

The energy demand distribution shows that the east part has a larger and denser energy demand than the west; meanwhile, land functions in the east are more mixed which leads to diversified energy load features. Therefore, the study zone is divided into two parts, show in figure 3, the east part (zone1) will adopt centralized energy system and the west part (zone2) will use discrete energy solution at plot level. Floor area of these two zones is 800,000m^2 and 90,000m^2 respectively.

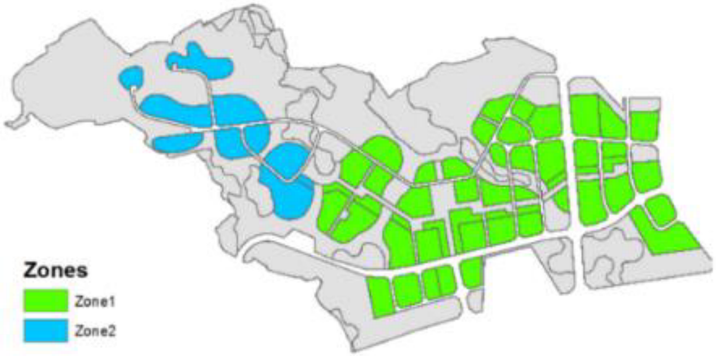

Figure 3. Classification of zones

By diagnosing the local renewable energy resources, both deep and shallow geothermal energy have application potential in the study zone. For deep geothermal energy, heat gradient in the study zone is 3.6°C per 100m depth, soil temperature could reach 100°C at 3km underground. Meanwhile, according to local geological data, it is suitable for geothermal drilling work. Thus, closed loop deep geothermal heat pump is considered as one heating solution. Local geological data also shows that abundant shallow soil-source geothermal energy exists in the study zone, so ground-coupled heat pump is another potential renewable technology.

Besides, roof solar and air-source heat pump are two other applicable energy resources in the zone. Meanwhile, due to the time-of-use electricity tariff in the city, thermal storage and power storage are regarded as potential solutions for increasing energy flexibility of local energy system.

By considering energy demand features and energy supply radius, maximum potential install capacity are detected for each technology and these values will be constraints when sizing energy system during optimization, table 1 shows the maximum install capacity of two zones.

Table 1. Maximum install capacity of Zones.

Energy Technology	Zone1 Max Capacity [MW or MWH]	Zone2 Max Capacity [MW or MWH]
Gas Engine	no limitation	-
Absorption Chiller	no limitation	-
Electric Chiller	no limitation	no limitation
Gas Boiler	no limitation	no limitation
Deep Geothermal	15	1.5
Shallow Geothermal	1	1
Air-source heat pump	no limitation	no limitation
Roof PV	2.4	0.3
Elec Battery	no limitation	no limitation
Heat/Cold Storage	102/42	10.2/4.2

No limitation on a technology means that the energy source is abundant and would be sufficient to cover the total demand, in our use-case, these sources are the power grid and the natural gas network. Geothermal energy and thermal storage are mainly limited by available space and distance to the load center. Theoretically, roof PV could be installed on any free roof. By evaluating the radiation potential and the roof structure of the study zone, only parts of the roof are selected as good places for this technology, otherwise the installation cost will increase, and the unit electricity production will decrease.

c. *Optimization Study*

The annual hourly energy demand and the energy technologies information are inputs of the optimization tool. To simplify the simulation work, 6 typical days and 4 extreme days are selected for each zone, show in figure 4. The selection of typical days and the associated weight, i.e., how many days it represents in a year, relies on an optimization.

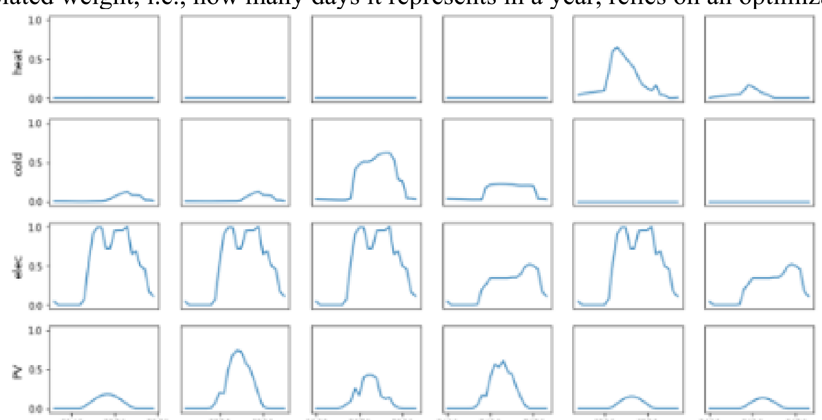

Figure 4. Load curve of typical days of zone1.

Besides, local energy prices, cost of energy equipment, energy efficiency, and other related hypothesis are shown in Tables 2 and 3.

Table 2. Cost of energy equipment.

Energy Technology	CAPEX [rmb/MW or MWh or m3]	Maintenance Cost per year [% of CAPEX]
Gas Engine	8,000,000	4%
Absorption Chiller	3,400,000	2%
Electric Chiller	1,600,000	2%
Gas Boiler	200,000	2%
Deep Geothermal	6,900,000	2%
Shallow Geothermal	4,600,000	2%
Air-source heat pump	2,550,000	2%
Roof PV	4,900,000	1%
Elec Battery	1,920,000	2%
Heat/Cold Storage	1,300	1%

Table 3. Current energy prices in the city.

Electricity price			
	Peak	Flat	Valley
Price [rmb/kWh]	1.1983	0.6657	0.3195
Peak period	10h-12h, 18h-22h		
Flat period	8h-10h, 12h-18h, 22h-24h		
Valley period	0h-8h		
Gas price			
Price [rmb/m^3]	3.094		

In this study, we also tested the impact of the renewable ratio on the economy of the whole energy system. Thus, in order to reach different renewable ratios, we extended the available roof surface for PV. The additional roofs have however lower solar radiation and small surface area which leads to higher unit cost and lower power production. Based on the local conditions, we defined three categories of roof for PV with the following maximum capacity and cost, shown in Table 4.

Table 4. Three levels of roof PV.

PV types	Zone1 Max Capacity [MW]	Zone2 Max Capacity [MW]	CAPEX [rmb/MW]
Low-cost PV	2.4	0.3	4,900,000
Middle cost PV	2.6	0.3	7,500,000
High-cost PV	7	1	9,000,000
Low-cost PV	2.4	0.3	4,900,000

Regarding calculation of the renewable energy ratio, different energy grades are taken into account. Meanwhile, primary energy efficiency is considered: only if the renewable technology has a higher primary energy efficiency than the business-as-usual solution (i.e., gas boiler for heating and electric chiller for cooling in our case study), such renewable technology is counted as an effective renewable energy [3].

The following equation is used for the renewable ratio calculation in our optimization:

$$Reneable\ ratio = \frac{Energy\ produced\ by\ renewablw * renewable\ share}{Total\ energy\ demand} \quad (1)$$

The renewable share of each renewable energy is obtained according to the equivalence conversion coefficient of its end-use energy and its energy efficiency. The renewable shares are shown in Table 5.

Table 5. Parameter of renewable share.

Technology	Renewable share
Deep geothermal for heating	0.63
Shallow geothermal for heating	0.45
Shallow geothermal for cooling	0.21
ASHP for heating	0.27
ASHP for cooling	0
PV for electricity	2.2

d. General Study

Based on all the inputs above, the optimization tool gives the technical solution with best economy for 20 years of service life.

Table 6 shows the optimal combination of technologies of zone1. Both heat and cold storages are installed at their maximum capacity. Traditional energy solutions are preferred in this case, both deep and shallow geothermal solution are abandoned by the tool. This shows these renewable solutions have less economic competitiveness in this zone. Total renewable ratio is 3.9%.

Table 6. Optimized installed capacity of zone1.

Installed heating capacity [MW or MWH]		Installed cooling capacity [MW or MWH]		Installed electricity capacity [MW or MWH]	
Gas Engine	7.14	Abs chiller	7.14	Gas engine	7.14
ASHP	8.38	ASHP	10.05	PV	2.4
Gas boiler	11.96	Elec chiller	48.3		
Heat storage	102	Cold storage	42		

Looking at the energy production of each technology, gas engine and ASHP have produced the most part of heat energy, gas boiler only contributed to 2% of total heat production, mainly during peak hours. Almost half of the heat energy produced has been stored first, show in figure 5.

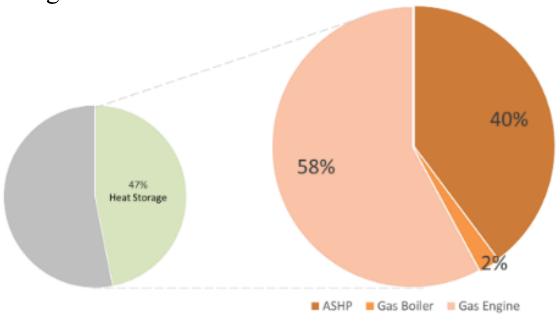

Figure5. Heat production structure of Zone1.

For cold energy production, electric chiller and absorption chiller undertake 66% and 34% of cold production respectively, ASHP only works for a few hours during high consumption days. A quarter of the cold energy has been stored, show in figure 6.

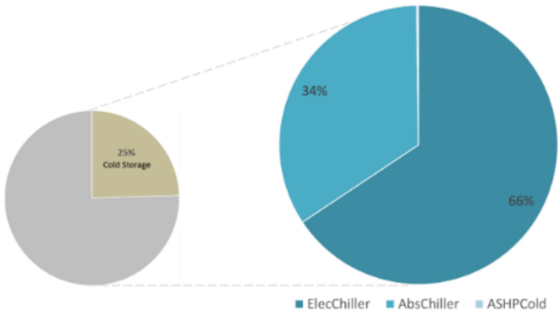

Figure 6. Cold production structure of Zone1.

Half of the electricity is produced by gas engines, roof PV contributes to another 4%, and the remaining part is purchased from grid. Due to the high cost of battery, all the electricity produced and purchased is directly consumed, show in figure 7.

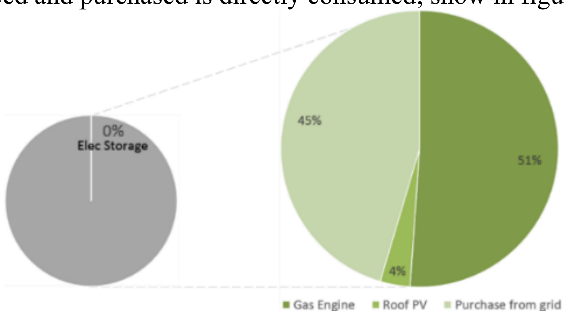

Figure 7. Electricity production structure of Zone1.

In zone2, the most economical technology structure is shown in table 7. Compared to zone1, energy demand is too small to adopt gas engine which has a high unit cost. Shallow geothermal heat pump is identified as a good solution in zone2, and thermal storage is installed.

Table 7. Optimized installed capacity of zone2.

Installed heating capacity [MW or MWH]		Installed cooling capacity [MW or MWH]		Installed electricity capacity [MW or MWH]	
Shallow geothermal	0.92	Shallow geothermal	0.966	PV	0.3
ASHP	0.475	ASHP	0.57		
Gas boiler	0.045	Elec chiller	1.855		
Heat storage	10.2	Cold storage	4.2		

Regarding the energy production, shallow geothermal heat pumps generate 77% and 55% of the total heat and cold energy respectively; ASHP and electric chiller produces most of the rest; gas boiler and ASHP undertake the sharp peak demand. Nearly 96% of electricity is purchased from the grid, roof PV supply 4% of the total electricity demand. Under this solution, the renewable ratio of zone2 is 12.5%.

e. Renewable Orientated Results

Sometimes, city may have a mandatory or expected target of renewable ratio. In this case, economy will not be the only priority during optimization, but still the optimization tool could find a best solution under a given renewable ratio target constraint.

In this study, several energy solutions are given under different renewable ratio targets to analyze the impact on the economy of the whole system.

The optimal energy solutions obtained under different renewable ratio are shown in figure 8, giving the unit cost and energy structure comparison of each scenario during the whole service life in the zone1.

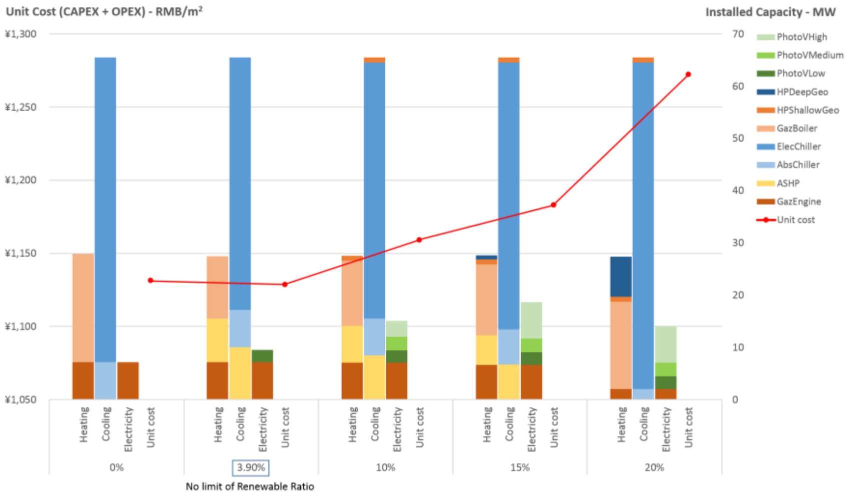

Figure 8. Unit cost and installed capacity of different renewable ratio in zone1.

In zone1, a certain part of renewable technology could improve the profit of the whole energy system; as the renewable ratio increases, the whole energy system will be more expensive, because high-cost PV and deep geothermal systems are built.

In zone2, the result shows the same trend, show in figure 9. When renewable ratio reaches 20% or a higher value, in order to satisfy such a high renewable ratio, the total installed capacity of heating is already more than the maximum demand, which means some equipment have to operate under low efficiency during certain period. Meanwhile, high-cost battery is installed to store superfluous electricity produced by roof PV.

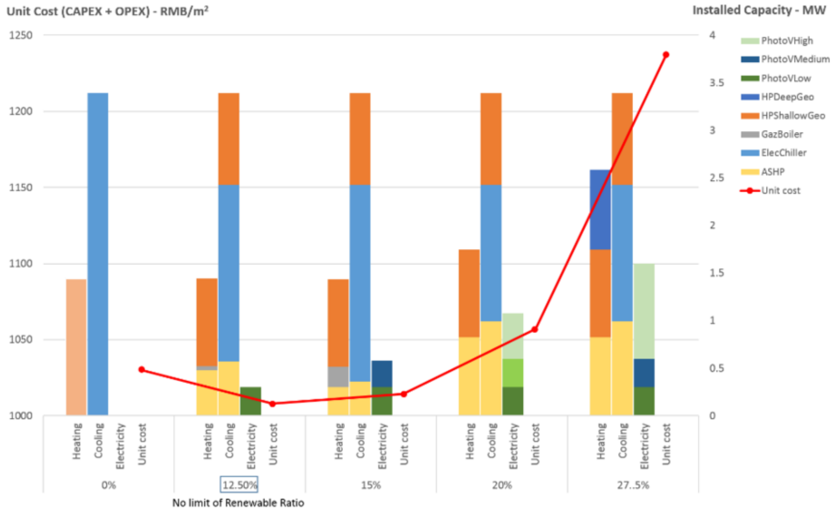

Figure 9. Unit cost and installed capacity of different renewable ratio in zone2.

f. Impact of Thermal Storage in Multi-Energy System

In the study project, thermal storage reached its maximum installable capacity in all the energy solutions; thermal storage has a clear positive impact on economy of our multi-energy system. In zone1, by integrating thermal storage, the cost of energy system is reduced by around 5% in all renewable ratio target scenarios, show in figure 10.

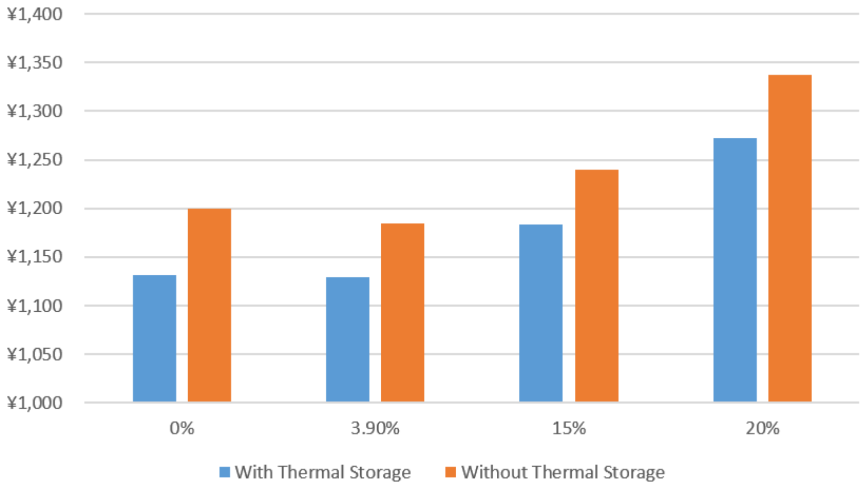

Figure 10. Impact of thermal storage on economy.

When looking at the electricity consumption, as shown in figure 11, the thermal storage can shift parts of the peak electricity consumption to valley or flat periods of electricity tariff. Meanwhile, the thermal storage optimizes the operation of the different energy equipment by allowing the efficient equipment to operate for longer hours, increasing the global energy efficiency. Thus, the total electricity consumption decreases at around 10%.

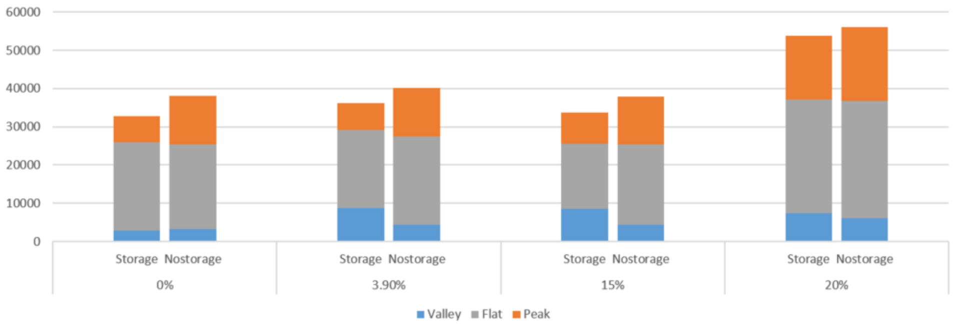

Figure 11. Impact of thermal storage on electricity consumption.

4. Conclusion

Cities have diversified energy demand profiles, both in time and space, and diversified local resources. The green and low-carbon development backed up by proactive policies unlocks the use of new technologies and new technologies combinations. This diversity of contexts and technical solutions greatly increases the complexity of urban energy planning. Optimization tools can bring a valuable support to guide the urban developers and designers to make sustainable energy choices from the early planning stage.

Until a certain renewable ratio, renewable energy is not only beneficial for the environment but also the most economical solution. Adapted choices in the urban planning phase can push further this point to increase the share of renewable energy that is economically accessible. The main levers are density of demand, mixity of functions, and localisation of consumption centres relative to the local resources. On the contrary, unreasonable renewable energy targets, not sufficiently considering local demand and resources, will increase the cost of energy system, and may damage the attractiveness of the new developed urban area.

According to the energy structure and local energy tariff, thermal storage could be a good solution in the multi-energy system to decrease both operation cost and investment of other equipment. This trend is expected to grow with the increasing need for integration of intermittent renewable energies.

Acknowledgment

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