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Integrated Planning for Urban Energy Systems with High Shares of Renewable Electricity

Zhihao Chen, Pei Liu*, Zheng Li, Weidou Ni

State Key Lab of Power Systems, Department of Energy and Power Engineering, Tsinghua University, Beijing 100084, China
liu_pei@tsinghua.edu.cn

With the process of low carbon transition of energy systems, renewables, particularly wind and solar, are seeing rapid growth these years. Due to the intermittency, high shares of renewable electricity would pose pressure on energy systems balance. Traditionally, systems rely on the flexible operation of thermal plants, which might be costly. A promising approach is to design and operate energy systems in an integrated manner. This paper proposed an integrated urban energy systems planning model, combining the processes of acquiring and using energy and including multiple energy systems in a single framework. A demand response module is inserted in the model, allowing part of the power load to be shifted to another period. The model is applied to a synthetic area with three regions, and ten scenarios are studied. The results illustrate that integrated planning and demand response program are beneficial for renewable electricity accommodation.

1. Introduction

The traditional energy supply system dominated by fossil fuels has caused a series of energy and environmental problems such as global climate change. To achieve sustainable development, many countries are vigorously developing renewable energy and promoting the low-carbon transition of energy systems. In 2018, shares of non-hydro renewables (mainly wind and solar power) in total primary energy consumption in China and the world were 4.4 % and 4.0 %. China is the largest contributor to renewables growth, with a growth rate of 41.4 % per annum between 2007 and 2017 (BP Group, 2019). However, the intrinsic intermittency of solar and wind power would pose pressure on the power balance. More flexibility is of vital importance for future urban energy systems with a higher proportion of renewable electricity.

In general, thermal power plants are used for power load dispatching (Chen et al., 2020). Integrated urban energy system (IUES) is regarded as a promising approach to further exploit the potential flexibility (Yang et al., 2018). On the one hand, it combines the processes of source-network-load-storage in the power sector. The variations of renewable electricity can be accommodated by not only power plants, but also through cross-region balance, demand-side management, as well as storage facilities. On the other hand, IUES broadens the feasible region of optimization by integrating multiple energy systems (such as power system, heating system, natural gas system) that are traditionally designed and operated independently.

Several models for integrated planning of urban energy systems are developed in recent years. Superstructure-based modelling is commonly used to contain all the alternative configurations and pathways in a systematic approach (Liu et al., 2011). However, most of the studies treat energy demand as fixed input, without considering the demand-side flexible potential (Keirstead et al., 2012). Loads such as industrial production, building air conditioning, and washing machine are adjustable (SGERI, 2019). Demand response (DR) programs let the demand side change its load pattern to adapt to the supply side through pricing or incentive-based mechanism (Mohammadi et al., 2017). Both demand and supply side may benefit from DR programs if they are well designed. This work proposed an integrated planning model for urban energy systems with high shares of renewables, taking multi-energy systems, multiple energy processes, and demand responses into system optimization. The model is introduced in section 2. A case study is used to illustrate the benefits of integrated energy planning, including the impacts of demand response. Conclusions are drawn in section 4.

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2. Methodology

In this section, the integrated urban energy systems (IUES) planning model is developed to address the problems introduced by high proportions of renewables. The structure and basic settings of the IUES model are described first, followed by the illustration of the objective function and main constraints.

2.1 Model description

The IUES model aims to produce holistic plans for energy infrastructure selection, sizing, and location. The superstructure-based modelling is adopted by the IUES model to contain multiple forms of energy in a framework and to realize the process-wide integration. Temporal features are considered by dividing a year into three seasons (winter, mid-season, summer), each of which is represented by a typical day. The IUES planning model is formulated as an optimization model, and the optimal solutions can be obtained by solving a mixed-integer linear programming (MILP) problem.

A demand response module is embedded in the IUES model. The power load in one period consists of a fixed part and a transferable part. Under the incentive-based response mechanism, electricity users can adjust their energy usage behaviour, and shift part of the transferable load from its original period to a new period, as shown in Figure 1. The energy system should offer payments to demand response participants in return for the flexibility they provided. The incentive mechanism proposed in this paper correlates the demand response payments to the load shifted ($edr_{s,h\to h',r}$) and time distance between two periods ($\Delta t_{h,h'}$), which will be explained in detail in the following part.

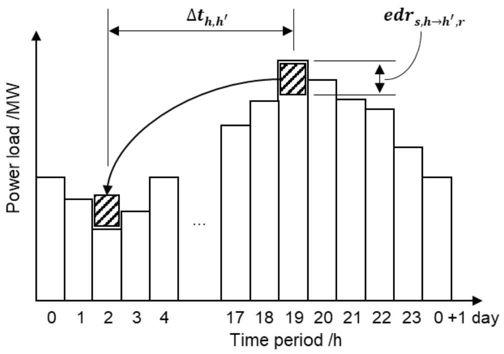


Figure 1: Schematic diagram of power demand response

2.2 Mathematical formulations

2.2.1 The objective function

Economic performance is the main consideration in energy system planning. The objective function of the IUES model is to minimize the annual total cost of the energy systems, expressed by Eq(1). The total cost (tc) consists of conversion technology cost (c_r^{cnv}), energy network cost (c_r^{net}), storage technology cost (c_r^{stt}), fuel cost (c_r^{fuel}), and demand response payments (c_r^{DR}).

$$tc = \sum_r (c_r^{cnv} + c_r^{net} + c_r^{stt} + c_r^{fuel} + c_r^{DR}) \tag{1}$$

2.2.2 The design and operation constraints

Energy balance is one of the most important physical constraints, as expressed by Eq(2). The definitions of the main variables and parameters are listed in Table 1.

$$\begin{aligned} & ef_{s,h,r,e}^{imp} + ef_{s,h,r,e}^{ons} + \left(\sum_{r'} ef_{s,h,r'\to r,e}^{tr} \cdot \eta_e^{tr} - \sum_{r'} ef_{s,h,r\to r',e}^{tr}\right) + \left(\sum_{cvt} ef_{cvt,s,h,r,e}^{out} - \sum_{cvt} ef_{cvt,s,h,r,e}^{in}\right) \\ & + \left(\sum_{stt} ef_{stt,s,h,r,e}^{out} - \sum_{stt} ef_{stt,s,h,r,e}^{in}\right) = DMD_{s,h,r,e} + \left(\sum_{h'} edr_{s,h'\to h,r} - \sum_{h'} edr_{s,h\to h',r}\right)^{only\ for\ Electricity} \end{aligned} \tag{2}$$

Table 1: The main variables and parameters in the IUES planning model

Symbol	Unit	Definition
$ef_{s,h,r,e}^{imp}$	MW	energy e imported from outside the area in season s period h region r
$ef_{s,h,r,e}^{ons}$	MW	energy e collected onsite in season s period h region r
$ef_{s,h,r\to r',e}^{tr}$	MW	energy e transported from region r to r' in season s period h
$ef_{cvt,s,h,r,e}^{in/out}$	MW	energy e input/output of conversion technology cvt in season s period h region r
$ef_{stt,s,h,r,e}^{in/out}$	MW	energy e input/output of storage technology stt in season s period h region r
$edr_{s,h\to h',r}$	MW	electricity shifted from period h to period h' in season s region r
η_e^{tr}	100 %	energy network transmission efficiency of energy e
$\Delta t_{h,h'}$	h	the time distance between period h and h'
$DAYS_s$	d	the number of days in season s
$DMD_{s,h,r,e}$	MW	the demand of energy e in season s period h region r
$PTL_{s,h,r}$	100 %	percentage of transferable load in original load in season s period h region r
$ULSP$	USD/(kW·hour)	unit load shifting payment

For electricity, demand response is considered in power balance. Eq(3) ensures that the power load shifted from period h to other periods is no more than a certain proportion ($PTL_{s,h,r}$) of the original power load ($DMD_{s,h,r}^{Electricity}$). The demand response module presented here assume that payments to the participants (c_r^{DR}) are proportional to the product of the load shifted ($edr_{s,h\to h',r}$) and the shifting distance ($\Delta t_{h,h'}$), expressed by Eq(4). Parameter $ULSP$ stands for the payment for shifting 1 kW 'one-hour distance'.

$$\sum_{h'} edr_{s,h\to h',r} \leq PTL_{s,h,r} \cdot DMD_{s,h,r}^{Electricity} \tag{3}$$

$$c_r^{DR} = \sum_{s} [DAYS_s \cdot \sum_{h,h'} (edr_{s,h\to h',r} \cdot \min\{\Delta t_{h,h'}, 24 - \Delta t_{h,h'}\} \cdot ULSP)] \tag{4}$$

The model also contains constraints of renewable electricity deployment target, operating capacity factor limits, load dispatching speed limits, and renewable availability.

3. Case study

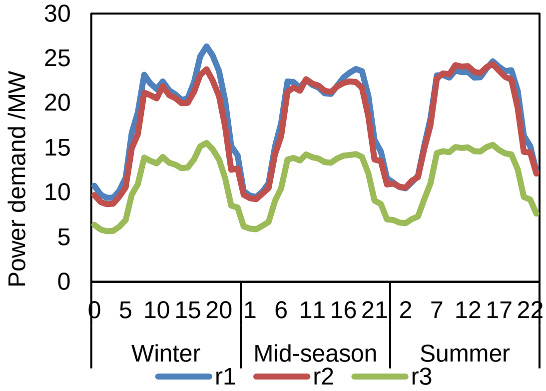
3.1 Case and scenario specifications

Currently, hourly demand data at the urban scale are difficult to obtain from public sources. Part of the heating demand and cooling demand is included in power consumption data. In this work, a synthetic urban area in North China is established. The synthetic area consists of three clusters, and their energy demand curves are calculated based on standard energy load index, time use survey, building energy demand simulation results, and statistic data of existing buildings, as illustrated in Figure 2.

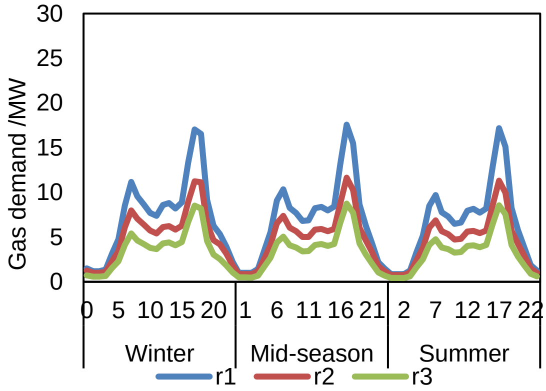
The IUES planning model is applied to the synthetic area to testify its functions and reveal the benefits of integrated planning. Ten scenarios have been set according to the renewable target, the proportion of transferable power load and the unit load shifting payment ($ULSP$), as listed in Table 2. The renewable targets are expressed as proportions of renewable electricity (solar and wind power) in primary energy consumption.

Table 2: Scenario Settings

Name of Scenario	Renewable Target	Demand Response Rate	$ULSP$ (USD per kW per hour distance)
R10-D0	10 %	0 %	-
R20-D0	20 %	0 %	-
R20-D5-P0	20 %	5 %	0
R20-D5-P1	20 %	5 %	0.01
R20-D5-P2	20 %	5 %	0.02
R20-D5-P5	20 %	5 %	0.05
R20-D10-P0	20 %	10 %	0
R20-D10-P1	20 %	10 %	0.01
R20-D10-P2	20 %	10 %	0.02
R20-D10-P5	20 %	10 %	0.05



(a)



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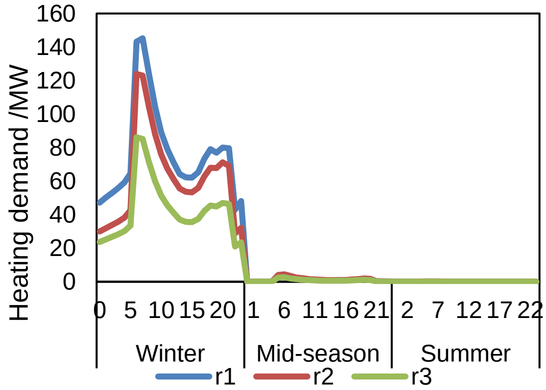

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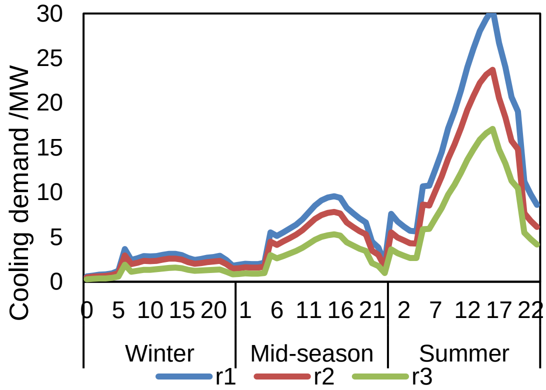

(d)

Figure 2: Energy demand curves of the synthetic urban area- (a) Power demand (b) Gas demand (c) Heating demand (d) Cooling demand

3.2 Results and discussion

3.2.1 The effects of the integrated planning

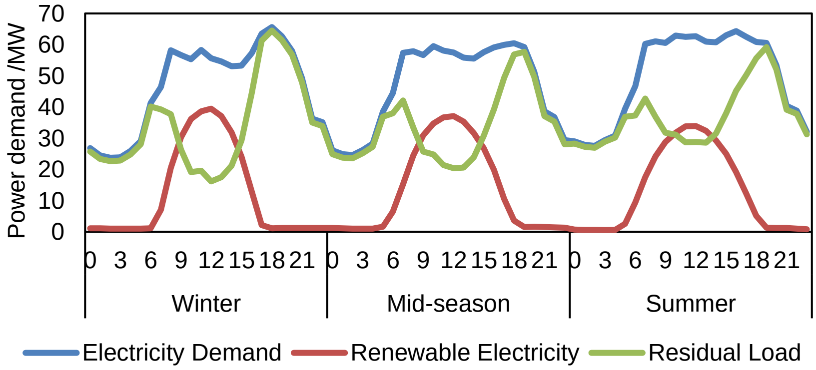

Figure 3: Impact of renewable electricity to original electricity demand, scenario R20-D0

High shares of renewables would change the electricity demand curve, as shown in Figure 3. At noon, when the photovoltaic (PV) output is high, the original load peak becomes net load valley. Table 3 lists the results of the IUES planning model under scenario R10-D0, R20-D0, and R20-D0 without cross-region connections. For scenario R20-D0, wind turbine, PV, NGCC, CCGT CHP, gas boiler, absorption chiller, air-source HP are to be built. Power grids connect r1 to r2, r1 to r3, and r2 to r3. Heat pipes connect r1 to r2, r2 to r3.

Table 3: The optimal energy system plans of the synthetic area

	Unit	R10-D0	R20-D0	R20-D0 (no transmission)
Wind turbine	MW	4.5	4.5	4.5
PV	MW	32.029	61.242	61.242
NGCC	MW	60	60	-
NGCT	MW	-	-	30
Gas turbine CHP	MW	10	-	20
CCGT CHP	MW	-	24	48
Coal boiler	MW	173.64	-	0.1
Gas boiler	MW	139.44	252.36	194.64
Absorption chiller	MW	38	20	46
Air-source HP	MW	34.8	89.4	104.4
Li-Battery	MW	-	-	7
Thermal storage	MW	-	-	1
Power grid	-	r1-r2,r1-r3,r2-r3	r1-r2,r1-r3,r2-r3	None
Heat pipeline	-	r2-r3	r1-r2,r2-r3	None
Annual cost	10^6 USD	36.562	44.644	51.119 (14.5 % ↑)
Annual CO_2 emission	10^3 t	368.338	244.304	244.304

Integrated urban energy systems help to adapt to the fluctuation caused by renewables. Figure 4 illustrates how the power balance of region 1 can be achieved. NGCC, the central power generation technology of region 1, adjusts its output in different periods. In most of the time-slots, electricity is distributed from region 1 to region 2 and 3 to satisfy their demands. While in other periods, electricity is transported in opposite directions. Networks allow proper energy distribution and complementation between regions. If the three regions are separated from each other, all of them have to build their own power plants (probably with smaller capacity), and this would lead to a 14.5 % rise in the cost of the whole system. Energy storage facilities are not chosen in scenario R20-D0 since they are not cost-competitive. However, if there is no cross-region energy connection, Li-Battery and thermal storage are needed, as shown in Table 3. Integrated energy systems are multi-energy systems. Through air-source HP, electricity is utilized to provide space heating in winter and space cooling in summer.
It is noteworthy that the renewable target is a significant indicator. From scenario R10-D0 to R20-D0, more renewable generation capacity is to be built, with a higher annual cost and a significantly lower CO_2 emission.

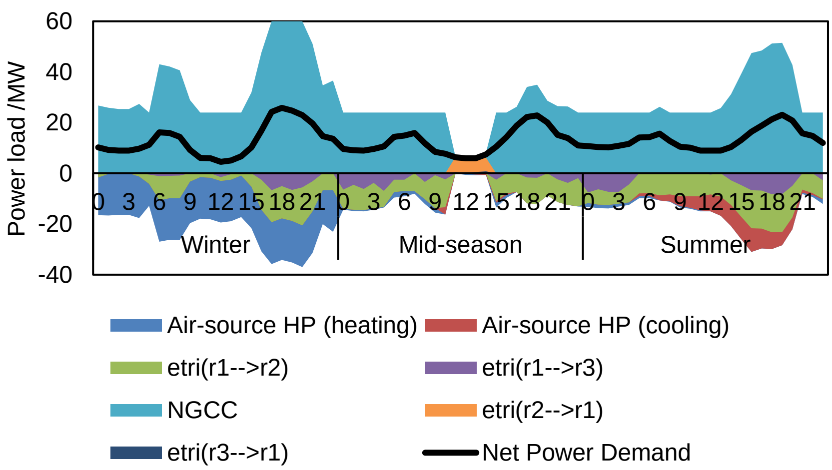

Figure 4: Power balance of region 1, scenario R20-D0

3.2.2 The benefits of demand response

The power demand response considered here is only the transfer of load, and the total power load is not reduced. The total costs of the system decline once demand response programs are introduced. In Figure 5, the leftmost column refers to scenario R20-D0. Demand response helps to realize energy balance at the optimum cost. For a certain level of load flexibility, the total cost decreases as the unit load shifting payment becomes lower. For the same level of unit load shifting payment, the total cost declines as the load transfer flexibility increases. Even with a price of 0.05 USD for shifting 1 kW load 'one-hour distance', the whole system can still benefit from demand response. Load shifting prices can be further determined based on the supply and demand conditions of flexibility resources.

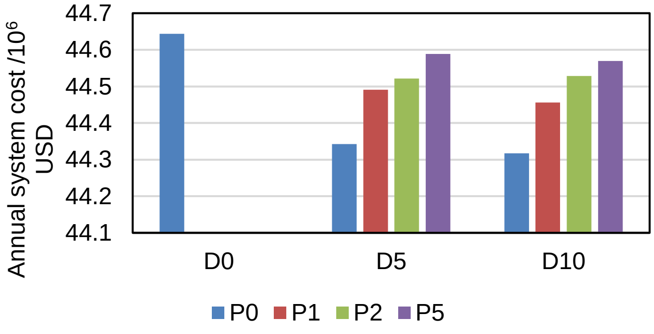

Figure 5: Annual system cost of different demand response scenarios, Renewable Target = 20 %

4. Conclusions

This paper presents the IUES planning model to find the optimal design and operation plans for urban energy systems with high shares of renewable electricity. A synthetic area consisting of three regions is used as a case study to reveal the benefits of integrated planning. Load dispatching of power plants, power flow through energy networks, energy storage and release, and conversion between different forms of energy jointly ensure the energy balance with the lowest cost. If the three regions are designed and operated separately, the total cost will increase by 14.5 %.

Demand response program in this paper allows end-users to re-allocate their power load, which provides more flexibility to the systems. The total cost of energy systems decreases as unit load shifting payment declines or the load shifting flexibility rises. Participants of demand response programs can get payments, and the systems can have a lower cost. The mechanism proposed still works when paying 0.05 USD for shifting 1 kW 'one-hour distance'.

Future works might improve integrated energy planning by considering more energy carriers, technologies, and sectors. The operational costs of energy conversion and storage should be more finely modelled. For demand response, the structure and flexibility ratio of the load at each period should be further studied. Broader demand response in which multiple energy demands response together might free up greater flexibility for renewables.

Acknowledgements

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