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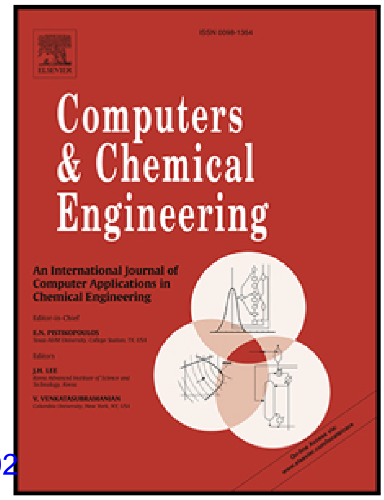

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Optimal Design of Integrated Urban Energy Systems Under Uncertainty and Sustainability Requirements

Zhihao Chen[a], Styliani Avraamidou[b], Pei Liu[a,*], Zheng Li[a], Weidou Ni[a], Efstratios N. Pistikopoulos[b,c]

a. Department of Energy and Power Engineering, Tsinghua University, Beijing, 100084, China
b. Texas A&M Energy Institute, Texas A&M University, College Station, TX 77843, USA
c. Artie McFerrin Department of Chemical Engineering, Texas A&M University, College Station, TX 77843, USA

Corresponding author

Pei Liu

Email address

Zhihao Chen, zh-chen16@mails.tsinghua.edu.cn

Styliani Avraamidou, styliana@tamu.edu

Pei Liu, liu_pei@tsinghua.edu.cn

Zheng Li, lz-dte@tsinghua.edu.cn

Weidou Ni, niwd@tsinghua.edu.cn

Efstratios N. Pistikopoulos, stratos@tamu.edu

Abstract

Large amounts of urban energy consumption and consequent environmental impacts are posing great pressure on sustainable development. Urban energy systems of the future should be designed in an integrated approach featuring enhanced economic and ecological performances. This work aims to develop a generic tool to support the optimal design of integrated urban energy systems. Methods of energy systems engineering are utilized to compose the tool, including superstructure-based modeling, mixed-integer linear programming, multi-objective optimization, and stochastic programming. The model is applied to facilitate the design of a newly planned urban region in North China. Results reveal trade-offs between system cost, carbon emission, and water consumption. Capability of integrated design is illustrated via multi-energy synthesis, process integration, and multi-regional interconnection. Considering uncertainties of renewables, more energy generation, conversion, and storage capacity are needed. The total cost expectation also increases. Ignoring uncertainties rooted in integrated urban energy systems might result in sub-optimal design.

Highlights

- A generic model for the optimal design of integrated urban energy systems is developed.
- Energy systems engineering approach methods are utilized to represent and address integrated urban energy design problems.
- Conflicts exist between economic and environmental criteria, and even between environmental criteria such as carbon emission and water consumption.
- Optimal design and planning need multi-energy coupling, process integration, multi-regional interconnection, and design and operation coordination.
- Uncertainty rooted in urban energy systems requires more energy generation, conversion, storage capacity, and higher cost to secure energy supply.

Keywords: Integrated urban energy system, Energy systems engineering, Energy system design, System optimization, Superstructure-based modeling, Energy-carbon-water nexus

1 Introduction

Energy is considered the lifeblood of modern society. However, the traditional way of energy production and consumption has caused severe environmental problems, such as global climate change (Johansson et al., 2012). Cities play a central role - they are homes to 55 percent of the global population (UN DESA, 2018), contribute 80 percent of the gross domestic production, consume two-thirds of primary energy, and are responsible for over 70 percent of greenhouse gas emissions (World Bank, 2019). Global and national targets of low-carbon development must be realized at the urban level. Thus, urban energy systems face a dual challenge – to reduce the negative externalities and, at the same time, satisfy the growing energy demand.

The forms of urban energy systems are continuously evolving. In the past, urban areas were regarded as energy consumers only. Power systems, gas systems, heating systems, and cooling systems were designed individually and operated separately (Yu et al., 2018). Nowadays, integration becomes a significant trend of urban energy systems. It happens in many aspects, including complementing multi-energy systems, combining different energy processes, synthesizing centralized and distributed generation, coordinating design and operation phases, and considering trade-offs of multiple criteria. An integrated urban energy system is a promising approach to improving system efficiency, promoting renewable energy utilization, and reducing cost and carbon emissions.

Recently, urban energy systems have attracted increasing research interest. Keirstead et al. (2012) clustered previous studies into six domains - technology design, building design, urban climate, systems design, policy assessment, and land-use and transportation modeling. Each domain varies by its specific research object, spatio-temporal scale, method, and how it represents an energy system's supply and demand sides. In this work, we mainly focus on energy systems design. A typical system design problem is determining the selection, capacity, layout, and construction time of energy equipment and networks to meet a set of energy service demands in a given area. An integrated urban energy system includes various energy carriers and technologies, pipeline network options, and considers economic, ecological, and social factors. Optimization methods are usually used to find the best possible solutions to facilitate the design of such complex systems.

A large number of mathematical models are developed to optimize urban energy systems. Liu et al. (2010) propose a superstructure-based modeling and optimization framework applied to a commercial building. Zheng et al. (2017) present an optimization toolkit for the combined cooling heating and power (CCHP) system. These models treat the research objects as a single entity and do not consider the areas' spatial division. Allen et al. (2019) develop a multi-region infrastructure planning model for power generation systems. The model enables cross-region power balance by constructing power grids, but it does not consider multiple energy demands. Zhou et al. (2013) provide a mixed-integer linear programming model for distributed energy systems. In this model, each technology's installed capacity may not equal an integer multiple of a single machine's capacity, and the start-stop action of the unit cannot be expressed. Economic performance is usually regarded as the objective of the optimization. Nowadays, environmental criteria are getting more attention, and energy-carbon-water nexus is becoming an important topic (Li et al., 2019). Meanwhile, the uncertainties introduced by renewable energy are considered in the optimization process. Mavromatidis et al. (2018) build a two-stage stochastic program to design distributed energy systems under uncertainty. However, this model is formulated for a specific energy system configuration, which can not be applied to a new case easily.

This work aims to develop a generic model for the optimal design of integrated urban energy systems. This model captures the main features of integrated urban energy systems, and the uncertainty and sustainability requirements are considered in this framework. The paper is structured as follows. The methodology is explained in detail in Section 2. A case study is presented in Section 3, followed by the results and discussion part in Section 4. Conclusions are drawn in Section 5.

2 Methodology

2.1 Modeling framework

Energy systems engineering methods provide a generic approach to address complex energy and environmental problems (Demirhan et al., 2019). Based on energy systems engineering methods, the model's structure in this work is illustrated in Fig. 1. The features of integrated urban energy systems are firstly contained in a superstructure. The superstructure representation is then expressed as a mixed-integer linear program, which can be solved to obtain optimal design and operating solutions. Multi-objective optimization and stochastic programming are implemented to reveal the impacts of sustainable requirements and uncertainties.

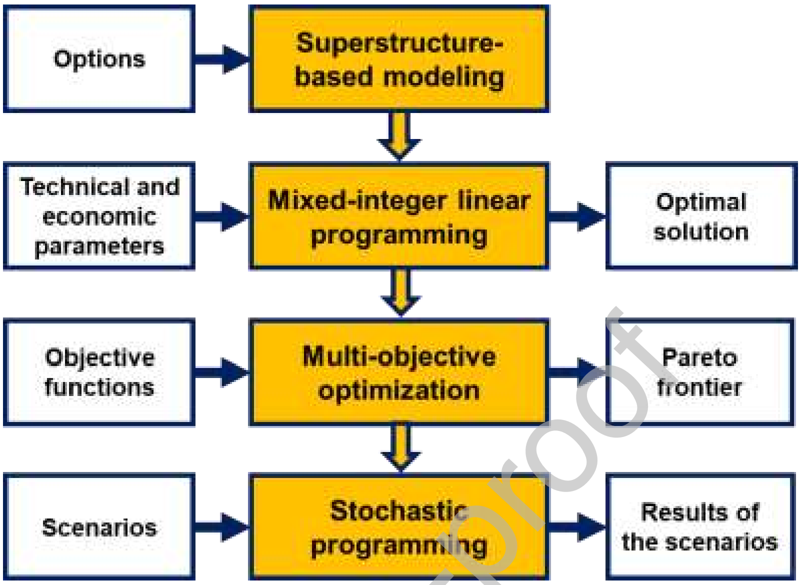


Fig. 1. Modeling processes under energy systems engineering approach

Spatio-temporal resolution is of vital importance in systems modeling and optimization. Energy resources and demand are distributed unevenly in space. Treating the city as a combination of regions rather than a single entity can grasp the spatial distribution of energy supply and demand and unlock the potential of synergies between regions.

The choice of model time scale depends on the characteristics of the modeled object. For the design of integrated urban energy systems, the construction and decommissioning of technologies and networks can be decided in units of years. However, the design plan should achieve the hourly supply and demand balance. On the demand side, energy consumption varies by season and changes in a single day. On the supply side, renewable generation technologies introduce intermittency and fluctuation to the systems.

2.2 Superstructure representation

The superstructure of integrated urban energy systems consists of all possible alternatives, including different energy sources and demands, energy processes, technology options, network configurations, operation mode, and the consequent energy flow pathways. In Fig. 2, the two white blocks represent two different regions inside the city. Energy can be imported from outside the city, collected onsite, or transmitted and distributed between regions through energy networks. Inside each region, there are energy generation, conversion, and storage sectors. Different varieties of primary energy (both renewable and non-renewable) are transformed into secondary energy (e.g., electricity, heat, and cooling) in the generation sector. In the conversion sector, secondary energy can be converted from one form into other forms. Storage facilities help to store the excess energy at a time for later use. These three sectors, as well as energy import and energy networks, work together to meet the final energy demand in each region.

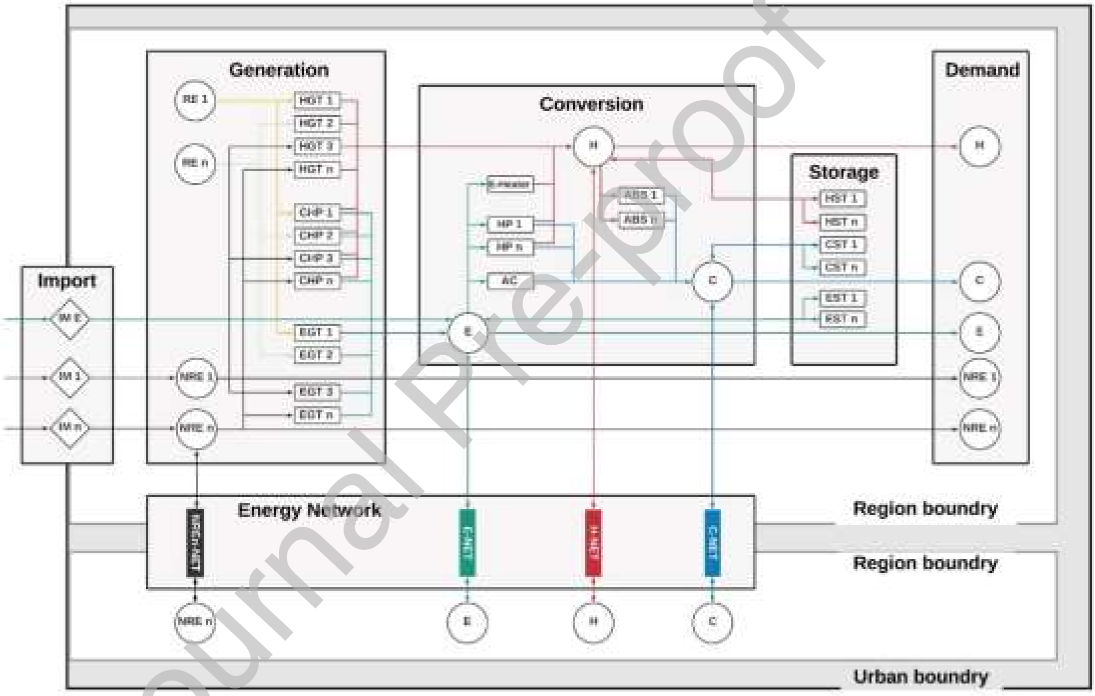


Fig. 2. Superstructure representation of integrated urban energy systems

2.3 Mathematical formulation

The superstructure representation illustrated above is transformed into a mixed-integer linear programming model. The quantities and relationships are expressed by variables, parameters, and algebraic equations.

2.3.1 Variables and parameters

The quantities involved in the model are divided into variables and parameters. Parameters are given as input data, including the unit capital costs, operation and maintenance costs, efficiencies, and lifetimes of energy infrastructures, as listed in Table A.1.

Variables are unknowns in the model. Continuous variables represent energy flow, economic cost, carbon emission, and water consumption, as listed in Table A.2. Integer variables are used to express the discrete decisions rooted in urban energy systems, include the number of units to be built in a year, and the number of operating units in a time-step, as listed in Table A.3. In this work, variables are expressed in lowercase and italic letters, while parameters are expressed in uppercase and regular letters to distinguish them.

2.3.2 Indices and superscripts

Most variables, parameters, and equations are defined on indices. An index is a set that contains a class of elements. For instance, index re stands for renewable energy, corresponding to solar, wind, biomass. All the indices used in this model are shown in Table A.4. Superscripts are used to define and interpret variables, as ted in Table A.5.

2.3.3 Equations

Algebraic equations are used to represent all the relationships in the superstructure. In optimization problems, equations are more commonly referred to as constraints. For a design problem of integrated urban energy systems, constraints can be classified into design constraints and operating constraints.

2.3.3.1 Design constraints

All the energy technologies and networks should be whole units. Eq.(1) and (2) ensure that a specific technology's installed capacity ($ic_{\mathrm{y,t,r}}$) is equivalent to multiples of a single unit's capacity ($\mathrm{SCAP_t}$). It is noteworthy that indices allow the modelers to create multiple equations using just one generic constraint. The same constraints can be applied directly to a full new case as long as the indices' elements are adjusted, and the corresponding parameter value of each element is updated. This feature greatly simplifies the modeling process and increases the generality of the model.

$$ic_{\mathrm{y,t,r}}^{\mathrm{new}} = iu_{\mathrm{y,t,r}}^{\mathrm{new}} \cdot \mathrm{SCAP_t} \tag{1}$$

$$ic_{\mathrm{y,t,r}}^{\mathrm{exist}} = iu_{\mathrm{y,t,r}}^{\mathrm{exist}} \cdot \mathrm{SCAP_t} \tag{2}$$

Technology units can be built during certain years of the planning period and then put into operation until they reach their lifetimes. For each type of technology, Eq. (3) connects the number of existing installed units ($iu_{\mathrm{y,t,r}}^{\mathrm{exist}}$) to the number of newly built units ($iu_{\mathrm{y',t,r}}^{\mathrm{new}}$) in previous years.

$$iu_{y,t,r}^{exist} = \sum_{y'=y-LF_t}^{y-1} iu_{y',t,r}^{new} \quad (3)$$

The three constraints above also apply to energy networks. The construction of various energy networks reflects the connection between regions, as shown in Eq. (4). The parameter $LINK_{n,r,r'}$ can be assigned to specify whether a certain energy network is allowed to be established between the two regions. Energy can flow in both directions in the energy network. Eq. (5) is used to remove the directionality in the network construction process.

$$iu_{y,n,r\to r'}^{new} \leq LINK_{n,r,r'} \cdot M \quad (4)$$

$$iu_{y,n,r\to r'}^{new} = iu_{y,n,r'\to r}^{new} \quad (5)$$

Some energy carriers can be imported from outside the city. Eq. (6) is used to restrict the number of import gate stations (NUM_e^{imp}). Binary variable $b_{r,e}^{imp}$ represents whether there is a gate station in region r.

$$\sum_r b_{r,e}^{imp} \leq NUM_e^{imp} \quad (6)$$

2.3.3.2 Operating constraints

Design and operating constraints correspond to different time scales. Operating constraints ensure that energy systems can operate normally within each time step and between adjacent time steps. Thus, indices s and h are used in the following equations.

Energy balances are the fundamental physical constraints. Eq. (7) is used to express the balance of a certain type of primary energy in each time-step. Primary energy can be imported from outside the city, transmitted between regions inside the city, collected onsite (such as distributed renewables), consumed by generation technologies or end-users. Eq. (8) shows the balance of secondary energy. Unlike primary energy, secondary energy can be produced by generation technologies, generated or consumed by conversion technologies, and stored or released by storage technologies. These two equations reveal the characteristics of integrated urban energy systems. Multiple energy carriers can be utilized, and multiple energy service demands should be satisfied. Processes of energy generation, conversion, storage, and transmission work together to balance the demand and supply.

$$ef^{\mathrm{imp}}_{\mathrm{y,s,h,r,pe}} + \sum_{\mathrm{r}',\mathrm{n}} (ef^{\mathrm{tr}}_{\mathrm{y,s,h,\,r'\to r,pe}} \cdot \eta_{\mathrm{n,pe}} - ef^{\mathrm{tr}}_{\mathrm{y,s,h,r\to r',pe}}) + ef^{\mathrm{onsite}}_{\mathrm{y,s,h,r,pe}} - \sum_{\mathrm{gnt}} ef^{\mathrm{gnt\_in}}_{\mathrm{y,s,h,r,gnt,pe}} = \mathrm{DMD}_{\mathrm{y,s,h,r,pe}} \tag{7}$$

$$ef^{\mathrm{imp}}_{\mathrm{y,s,h,r,se}} + \sum_{r',n} (ef^{\mathrm{tr}}_{\mathrm{y,s,h,r'\to r,se}} \cdot \eta_{\mathrm{n,se}} - ef^{\mathrm{tr}}_{\mathrm{y,s,h,r\to r',se}}) + \sum_{gnt} ef^{\mathrm{gnt\_out}}_{\mathrm{y,s,h,r,gnt,se}} + \sum_{cvt} (ef^{\mathrm{cvt\_out}}_{\mathrm{y,s,h,r,cvt,se}} - ef^{\mathrm{cvt\_in}}_{\mathrm{y,s,h,r,cvt,se}}) + \sum_{stt} (ef^{\mathrm{stt\_discharge}}_{\mathrm{y,s,h,r,stt,se}} - ef^{\mathrm{stt\_charge}}_{\mathrm{y,s,h,r,stt,se}}) = \mathrm{DMD}_{\mathrm{y,s,h,r,se}} \tag{8}$$

Characteristics of energy technologies are critical operating constraints. Eq. (9) and (10) represent the relationship between the inlet and outlet energy flows of energy generation and conversion technologies. Most of the technologies have a single input and a single output, while combined heat and power technologies generate heat and power at the same time. Eq.(9) is compatible with both types of technologies.

$$\sum_{\mathrm{e}} ef^{\mathrm{gnt\_in}}_{\mathrm{y,s,h,r,gnt,e}} \cdot \eta_{\mathrm{gnt,e'}} = ef^{\mathrm{gnt\_out}}_{\mathrm{y,s,h,r,gnt,e'}} \tag{9}$$

$$\sum_{\mathrm{e}} ef^{\mathrm{cvt\_in}}_{\mathrm{y,s,h,r,cvt,e}} \cdot \eta_{\mathrm{cvt,e'}} = ef^{\mathrm{cvt\_out}}_{\mathrm{y,s,h,r,cvt,e'}} \tag{10}$$

Generation and conversion technologies can only operate within specific load ranges. For renewable generation technologies, the upper bound of energy output is limited by resource availability ($\mathrm{RA}_{\mathrm{y,s,h,r,rgt}}$), as shown in Eq. (11). For generation technologies not belonging to renewables or CHP, they can operate between full load and minimum load level, expressed by Eq. (12). For CHP units, the nominal capacity usually refers to electric output, as illustrated in Eq. (13). Eq. (14) shows the operating ranges of conversion technologies.

$$\sum_{\mathrm{e}} ef^{\mathrm{gnt\_out}}_{\mathrm{y,s,h,r,rgt,e}} \le ou^{\mathrm{on}}_{\mathrm{y,s,h,r,rgt}} \cdot \mathrm{SCAP}_{\mathrm{rgt}} \cdot \mathrm{RA}_{\mathrm{y,s,h,r,rgt}} \tag{11}$$

$$ou^{\mathrm{on}}_{\mathrm{y,s,h,r,nnt}} \cdot \mathrm{SCAP}_{\mathrm{nnt}} \cdot \mathrm{LOL}_{\mathrm{nnt}} \le \sum_{\mathrm{e}} ef^{\mathrm{gnt\_out}}_{\mathrm{y,s,h,r,nnt,e}} \le ou^{\mathrm{on}}_{\mathrm{y,s,h,r,nnt}} \cdot \mathrm{SCAP}_{\mathrm{nnt}} \tag{12}$$

$$ou^{\mathrm{on}}_{\mathrm{y,s,h,r,chp}} \cdot \mathrm{SCAP}_{\mathrm{chp}} \cdot \mathrm{LOL}_{\mathrm{chp}} \le ef^{\mathrm{gnt\_out}}_{\mathrm{y,s,h,r,chp,"elec"}} \le ou^{\mathrm{on}}_{\mathrm{y,s,h,r,chp}} \cdot \mathrm{SCAP}_{\mathrm{chp}} \tag{13}$$

$$ou^{\mathrm{on}}_{\mathrm{y,s,h,r,cvt}} \cdot \mathrm{SCAP}_{\mathrm{cvt}} \cdot \mathrm{LOL}_{\mathrm{cvt}} \le \sum_{e} ef^{\mathrm{cvt\_out}}_{\mathrm{y,s,h,r,cvt,e}} \le ou^{\mathrm{on}}_{\mathrm{y,s,h,r,cvt}} \cdot \mathrm{SCAP}_{\mathrm{cvt}} \tag{14}$$

Each unit has a state at a particular moment, either in operation or out of service. Eq. (15) ensures that the number of units in operation cannot exceed the number of units in the current year. The state of each unit can change between two time-blocks. The number of units in operation depends on the previous time-slot actions, as shown in Eq. (16). In each region, units of one type are not allowed to start-up and shut-down at the same time, defined by Eq. (17).

$$ou_{\mathrm{y,s,h,r,t}}^{\mathrm{on}} \leq iu_{\mathrm{y,t,r}}^{\mathrm{exist}} \tag{15}$$

$$ou_{\mathrm{y,s,h+1,r,t}}^{\mathrm{on}} = ou_{\mathrm{y,s,h,r,t}}^{\mathrm{on}} + ou_{\mathrm{y,s,h,r,t}}^{\mathrm{start\_up}} - ou_{\mathrm{y,s,h,r,t}}^{\mathrm{shut\_down}} \tag{16}$$

$$ou_{\mathrm{y,s,h,r,t}}^{\mathrm{start\_up}} \cdot ou_{\mathrm{y,s,h,r,t}}^{\mathrm{shut\_down}} = 0 \tag{17}$$

For energy storage technology, energy can flow in and out and be stored in the device for some time. Eq. (18) shows that energy stored in a storage device in a certain period ($str_{\mathrm{stt,s,h+1,r,e}}$) is jointly determined by the energy stored in the previous period ($str_{\mathrm{stt,s,h,r,e}}$) and the energy input ($ef_{\mathrm{stt,s,h+1,r,e}}^{\mathrm{stt\_charge}}$) and output ($ef_{\mathrm{stt,s,h+1,r,e}}^{\mathrm{stt\_discharge}}$) in the current period. In Eq. (18), parameters $\eta_{\mathrm{stt}}^{\mathrm{self\_discharge}}$, $\eta_{\mathrm{stt}}^{\mathrm{stt\_charge}}$, and $\eta_{\mathrm{stt}}^{\mathrm{stt\_discharge}}$ refer to self-discharging losses, charging efficiency, and discharging efficiency. Eq. (19) ensures that the energy stored in the devices will not exceed the total capacity of energy storage technology.

$$str_{\mathrm{stt,s,h+1,r,e}} = str_{\mathrm{stt,s,h,r,e}} \cdot \eta_{\mathrm{stt}}^{\mathrm{self\_discharge}} - \frac{ef_{\mathrm{stt,s,h+1,r,e}}^{\mathrm{stt\_discharge}} \cdot \Delta\mathrm{H}}{\eta_{\mathrm{stt}}^{\mathrm{stt\_discharge}}} + ef_{\mathrm{stt,s,h+1,r,e}}^{\mathrm{stt\_charge}} \cdot \Delta\mathrm{H} \cdot \eta_{\mathrm{stt}}^{\mathrm{stt\_charge}} \tag{18}$$

$$str_{\mathrm{stt,s,h,r,e}} \leq ic_{\mathrm{y,stt,r}}^{\mathrm{exist}} \cdot \mathrm{DURATION}_{\mathrm{stt}} \tag{19}$$

The energy carriers realize cross-regional flow through energy networks. Energy flow is limited by the network capacity, as expressed by Eq. (20). Eq. (21) states that energy can flow in only one direction in a time step.

$$\sum_{\mathrm{e}} ef_{\mathrm{y,s,h,r'\to r,e}}^{\mathrm{tr}} \leq ic_{\mathrm{y,n,r'\to r}}^{\mathrm{exist}} \tag{20}$$

$$ef_{\mathrm{y,s,h,r'\to r,e}}^{\mathrm{tr}} \cdot ef_{\mathrm{y,s,h,r\to r',e}}^{\mathrm{tr}} = 0 \tag{21}$$

Energy imported from outside the city in a time step is restricted by Eq. (22).

$$ef^{\mathrm{imp}}_{\mathrm{y,s,h,r,e}} \leq b^{\mathrm{imp}}_{\mathrm{r,e}} \cdot \mathrm{IMP}^{\mathrm{upper}}_{\mathrm{r,e}} \tag{22}$$

The construction of energy technology needs space, which should not be ignored in urban energy planning. In particular, renewable generation technologies need more room since the resource density of renewables is relatively low. Eq. (23) represents the land constraint of energy technology.

$$ic^{\mathrm{exist}}_{\mathrm{y,t,r}} \cdot \mathrm{LAND}_{\mathrm{t}} \leq \mathrm{AREA}_{\mathrm{r}} \cdot \mathrm{PERCENT}_{\mathrm{t,r}} \tag{23}$$

Most of the equations above are linear constraints, except for Eq. (17) and (21). Non-linearity will increase the computation significantly, so it needs to be linearized. Eq. (17) can be replaced by Eq. (24), (25), and (26). Eq. (21) can also be transformed into several linear equations.

$$ou^{\mathrm{start\_up}}_{\mathrm{y,s,h,r,t}} \leq b^{start\_up}_{\mathrm{y,s,h,r,t}} \cdot M \tag{24}$$

$$ou^{\mathrm{shut\_down}}_{\mathrm{y,s,h,r,t}} \leq b^{shut\_down}_{\mathrm{y,s,h,r,t}} \cdot M \tag{25}$$

$$b^{start\_up}_{\mathrm{y,s,h,r,t}} + b^{shut\_down}_{\mathrm{y,s,h,r,t}} \leq 1 \tag{26}$$

2.3.4 Objective functions

Integrated urban energy systems are typical socio-technical systems. Several factors should be considered during the design process, including economic performance, carbon emission, resource consumption. Focusing on one criterion without considering the others will not yield satisfactory design results.

The energy system's total cost is a commonly used optimization goal, given by Eq. (27). The annual total cost consists of capital expenditure, operating and maintenance cost, and fuel cost, as expressed by Eq. (28).

$$tc = \sum_{\mathrm{y}} atc_{\mathrm{y}} \cdot \frac{1}{(1+\mathrm{I})^{\mathrm{y}-1}} \tag{27}$$

$$atc_{\mathrm{y}} = ac^{\mathrm{capex}}_{\mathrm{y}} + ac^{\mathrm{om}}_{\mathrm{y}} + ac^{\mathrm{fuel}}_{\mathrm{y}} \tag{28}$$

With the growing concern of global climate change, carbon emission has become an essential environmental criterion. The total carbon emissions during the planning period are equal to the sum of emissions each year, as shown in Eq. (29). The transition of energy structure and the promotion of carbon capture and storage (CCS) technologies help decarbonize the entire energy systems, as illustrated by Eq. (30).

$$te = \sum_{y} ate_{y} \tag{29}$$

$$ate_{y} = \sum_{r}\sum_{e}\sum_{s}\sum_{h} \mathrm{CEI_e} \cdot ef^{\mathrm{imp}}_{\mathrm{y,s,h,r,e}} \cdot \Delta\mathrm{H} \cdot \mathrm{DAYS_s} - \sum_{r}\sum_{e}\sum_{s}\sum_{h}\sum_{ccs} \mathrm{CEI_e} \cdot ef^{\mathrm{gnt\_in}}_{\mathrm{y,s,h,r,ccs,e}} \cdot \Delta\mathrm{H} \cdot \mathrm{DAYS_s} \cdot 90\% \tag{30}$$

Another critical but often ignored factor is the energy-water nexus. Energy supply requires water consumption, which may exacerbate urban water shortages. The total water consumption and annual total water consumption by urban energy systems are calculated by Eq. (31) and (32).

$$tw = \sum_{y} atw_{y} \tag{31}$$

$$atw_{y} = \sum_{gnt}\sum_{r}\sum_{s}\sum_{h} \mathrm{WATER_{gnt}} \cdot ef^{\mathrm{gnt\_out}}_{\mathrm{y,s,h,r,gnt,e}} \cdot \Delta\mathrm{H} \cdot \mathrm{DAYS_s} \tag{32}$$

Multi-objective optimization can simultaneously optimize a problem with two or more conflicting criteria. Epsilon−constraint method is widely used in multi-objective optimization problems (Haimes, 1971). It leaves only one objective function and converts other functions into constraints bounded by an epsilon value. In this way, a multi-objective optimization problem is transformed into a single-objective optimization problem with epsilon parameters. The optimal solutions to this problem from different values of epsilon parameters form the Pareto Front, which reveals the trade-offs between different criteria.

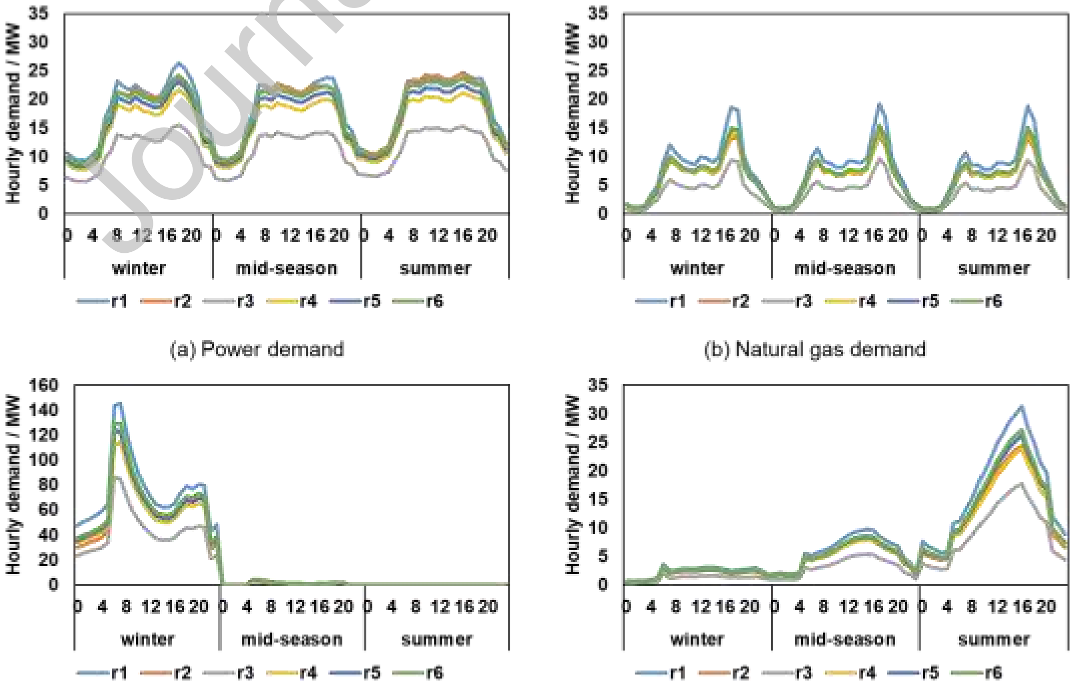
So far, the generic optimization model for integrated urban energy systems planning is established. Superstructure-based modeling is applied to capture the significant characteristics of integrated urban energy systems systematically. The model is formulated as a mixed-integer linear programming model, implemented on the General Algebraic Modeling Systems (GAMS) platform.

2.4 Optimization under uncertainty

Two-stage stochastic programming is the most common method to deal with uncertainty. The variables are classified into two groups, first-stage, and second-stage variables. First-stage variables correspond to “here-and-now” decisions, which are made before the realization of uncertainty. Second-stage variables correspond to “wait-and-see” decisions, which are made after uncertainty is revealed. In the integrated urban energy systems planning problems, design variables are usually first-stage variables, while operating variables are second-stage variables. The two-stage stochastic programming problem is also built in GAMS platform.

3 Case specification

Urbanization is a global trend. The world’s cities are growing in both size and number (UN DESA, 2018). Newly-built urban areas, towns, and parks provide opportunities for applying and promoting integrated energy systems planning. A new urban area situated in North China is chosen as an illustrative example. This new area consists of six regions. Each year is divided into three seasons: summer, mid-season, and winter. A typical day is selected for each season, and it is further subdivided into 24 hours. The new area’s hourly energy demands are estimated according to the areas of different types of buildings and the unit area energy consumption index. Fig. 3 shows the power demand, natural gas demand, heating demand, and cooling demand profiles of six regions.



(a) Power demand (b) Natural gas demand

(c) Heating demand (d) Cooling demand

Fig. 3. Energy demands of the new area

Multiple energy sources are considered to meet these energy needs, including natural gas, nuclear, and electricity imported from outside the new area, as well as onsite solar and wind power. Energy generation, conversion, and storage equipment can be built within the regions, and energy networks can be established to connect different regions. Table 1 lists the thirteen energy generation technologies considered in this work, including utility-scale, commercial scale, and domestic scale options. Tables 2, 3, and 4 introduce four conversion technologies, three storage technologies, and four energy networks.

Table 1. Energy generation technology options

Symbol	Technology	Scale
NGCT	Natural gas combustion turbine	utility
NGCT_CHP	Natural gas combustion turbine combined heat and power	utility
NGCC	Natural gas combined cycle	utility
NGCC_CHP	Natural gas combined cycle combined heat and power	utility
NGCC_CCS	Natural gas combined cycle with carbon capture and storage	utility
NUCLEAR	Nuclear plant	utility
PV_u	Photovoltaic	utility
WT	Wind turbine	utility
ICE_CHP	Internal combustion engine combined heat and power	commercial
CB_c	Coal boiler	commercial
GB_c	Gas boiler	commercial
PV_d	Photovoltaic	domestic
GB_d	Gas boiler	domestic

Table 2. Energy conversion technology options

Symbol	Technology
ASHP	Air-source heat pump
GSHP	Ground-source heat pump
ABS_CHILLER	Absorption chiller
AC	Air conditioner

Table 3. Energy storage technology options

Symbol	Technology
BATTERY	Li-battery
TES	Thermal storage
ICE	Ice storage

Table 4. Energy network options

Symbol	Technology
E_NET	Power grid
G_NET	Gas pipeline
H_NET	Heat pipeline
C_NET	Cool pipeline

The technical and economic parameters such as efficiency, lifetime, capital expenditure, fixed and variable operating cost are mainly collected from IEA-ETSAP and 2019 Annual Technology Baseline (NREL, 2019). Solar and wind resource availability data are found from Pfenninger and Staffell (2016). Carbon dioxide emission indices are adopted from 2018 Energy Data (Wang, 2018). Water consumption data are gathered from Gerdes and Nichols (2009) and UCS (2013).

These alternatives to energy carriers and infrastructures provide a vast array of possible system combinations. The optimization approach for integrated urban energy systems planning presented in Section 2 is applied to find the new area's best solutions. The results are illustrated in the next section.

4 Results and discussion

4.1 Trade-offs among economic and environmental criteria

Total system cost and carbon emission are chosen as objective functions of this new area, and water consumption is regarded as another important indicator. Fig. 4 shows the Pareto Front of multi-objective optimization. The black dots in the figure correspond to Pareto optimal solutions, while blue bubbles around them represent the system water consumption. With the tightening of carbon emission constraints, the system's total cost rises, and the increased rate is accelerating. However, the variation in water consumption at these design points is not monotonous. As carbon emissions decline, the system's water consumption drops slightly at first and then increases significantly.

Fig. 5 and Fig. 6 illustrate the installed capacity and cost composition of three design points. From design point A to B, coal boilers are replaced by gas boilers, and PV and CHP replace part of NGCC capacity. These changes consume less water and emit less carbon dioxide. To further decarbonize the energy systems, NGCC plants should add CCS technology and finally be replaced by nuclear plants, both of which options are water hunger. For design point C, nuclear power becomes the main power supply, and heat pumps meet cooling and heating demands. This solution requires higher capital expenditure and operating and maintenance costs but lower fuel cost.

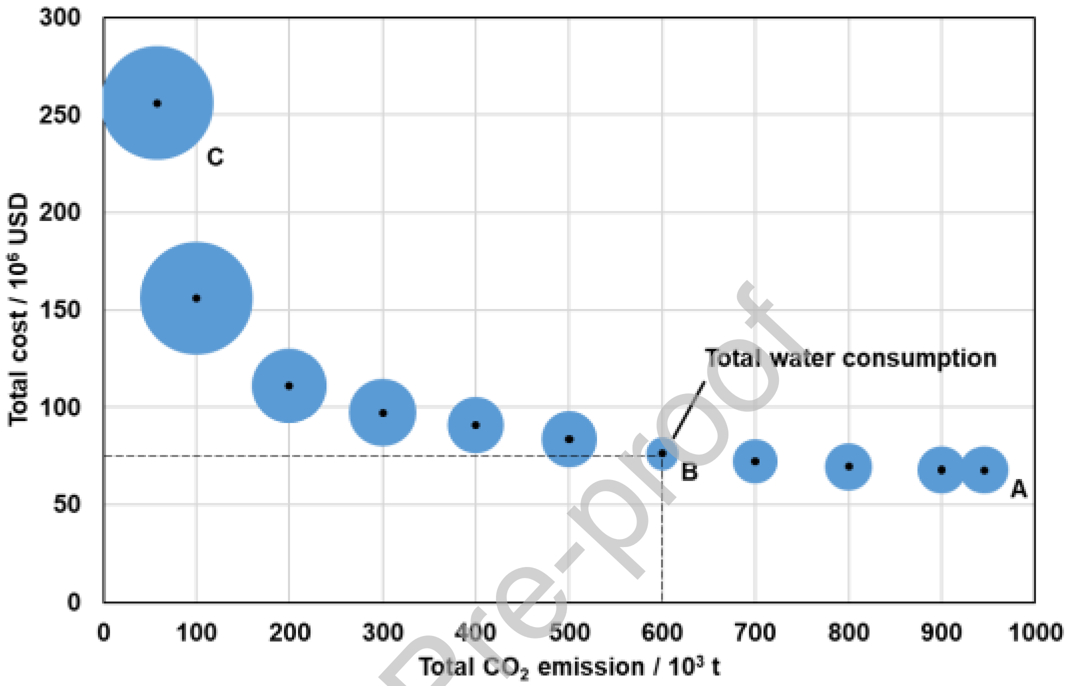


Fig. 4. The Pareto Front of system cost and CO_2 emission

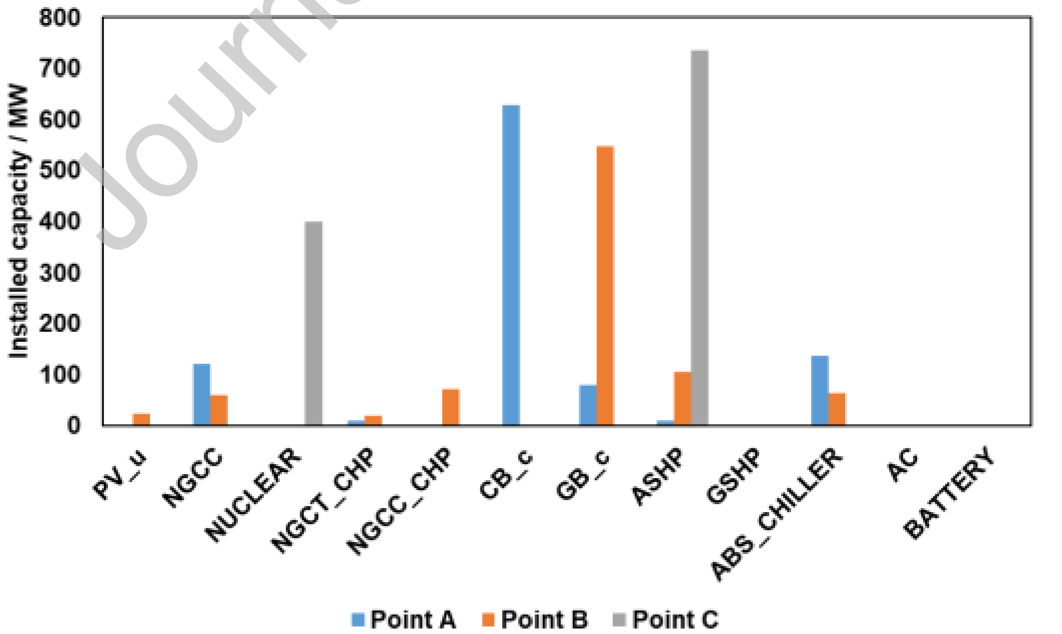


Fig. 5. The installed capacity composition of design point A, B, and C

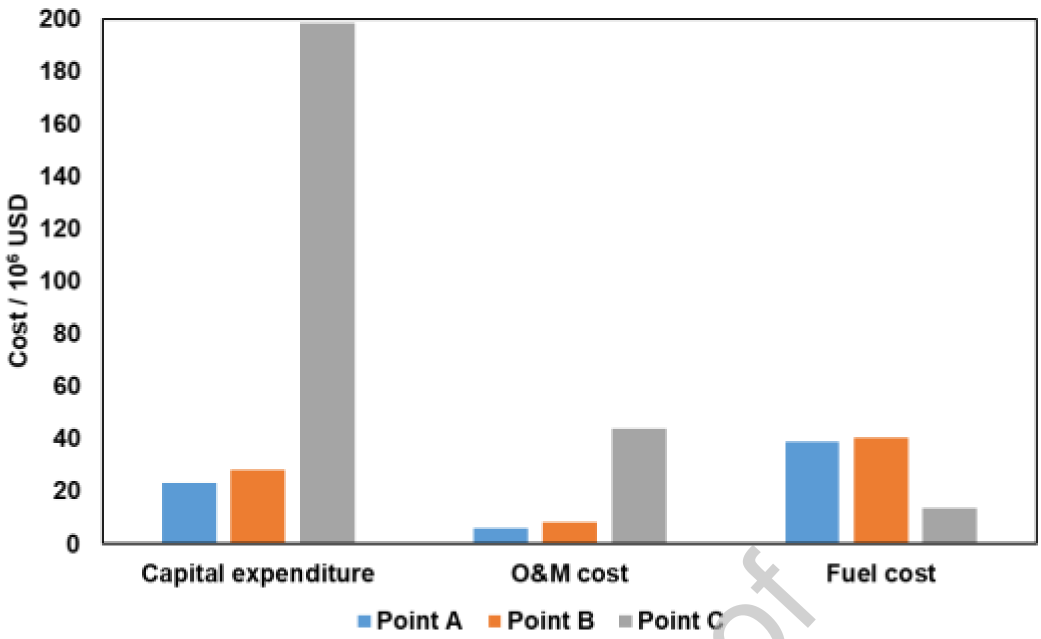


Fig. 6. Cost composition of design point A, B, and C

4.2 Design and operating solutions

The decision-makers can select appropriate design points according to their specific interests or considerations. Each design point corresponds to a complete design plan and operation schemes. In this case study, compared with design point A, the carbon emission and water consumption at design point B decreased by 36.5 % and 52.6 %, respectively, with the total cost increased by only 13.7 %. Thus, design point B is a relatively appropriate scenario and is used as an example here.

Centralized and distributed energy generations are integrated into the optimization model. The energy technology configuration of design point B is shown in Table 5. Generation technologies such as PV_u, NGCC, NGCT_CHP, NGCC_CHP, GB_c, and conversion technologies such as ASHP and ABS_CHILLER are chosen. No storage facilities are deployed, which means that energy storage options are not cost-competitive in design point B. The energy network layout of design point B is illustrated by Fig. 7. The thick arrows refer to energy flow imported from outside the new area. Power grids and natural gas pipelines are to be constructed to connect six regions. These networks allow the re-distribution of energy among different regions. Heating pipelines only deployed between region 1 and 6, and between region 5 and 6. No cooling networks exist, which means that cooling demands are all satisfied by onsite conversion technologies.

Table 5 – The installed capacity of six regions (Unit: MW)

	r1	r2	r3	r4	r5	r6
PV_u	5	4	2	4	4	4
NGCC	-	-	-	-	60	-
NGCT_CHP	5	5	5	-	-	5
NGCC_CHP	24	12	12	12	-	12
GB_c	89.52	95.88	59.28	94.32	107.88	100.44
ASHP	32.7	14.7	12.9	12.3	16.8	15.3
ABS_CHILLER	13	11	9	11	9	11

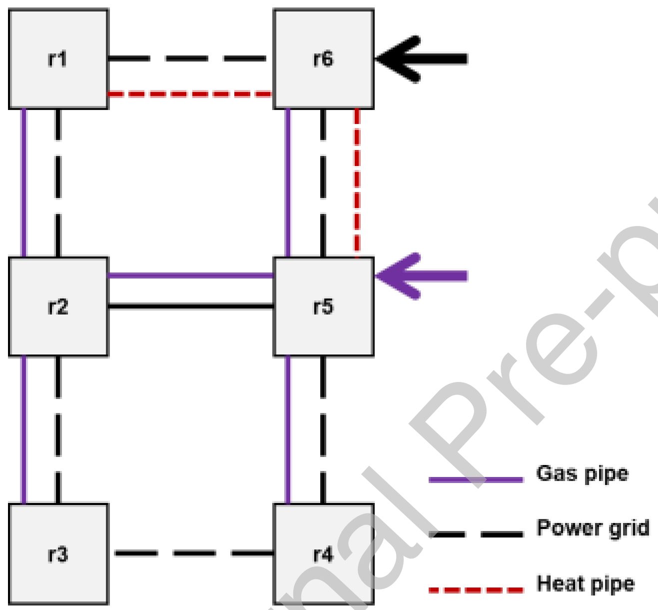


Fig. 7. The layout of energy networks, design point B

The yearly planning decisions are coordinated with hourly operating constraints. Fig. 8 shows the operating states of heat pumps in different seasons and hours. Most heat pump units operate in heating mode in winter, in cooling mode in summer, and few operate in the mid-season. The number of units in operation and the output of technologies vary in different hours and seasons to satisfy the variable demand. Fig. 9 expresses the hourly power balance in region 1 as an example. The red line refers to the power demand. The color pieces above the x-axis stand for power generated or transmitted into this region, while the color pieces below the x-axis stand for power consumed or transmitted out of this region. On the one hand, this graph indicates that the design point's technologies and networks can meet the operational requirements. On the other hand, it confirms that the optimal urban energy systems must be designed in an integrated approach, including multiple forms of energy, multiple technologies, multiple process, and multiple regions.

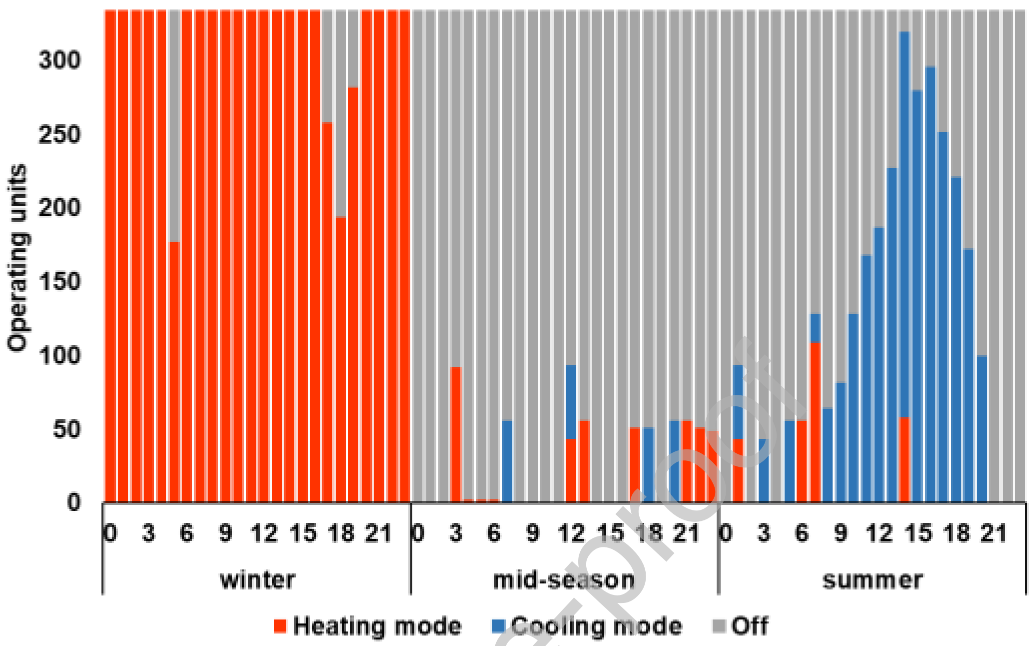


Fig. 8. Operating states of heat pumps, design point B

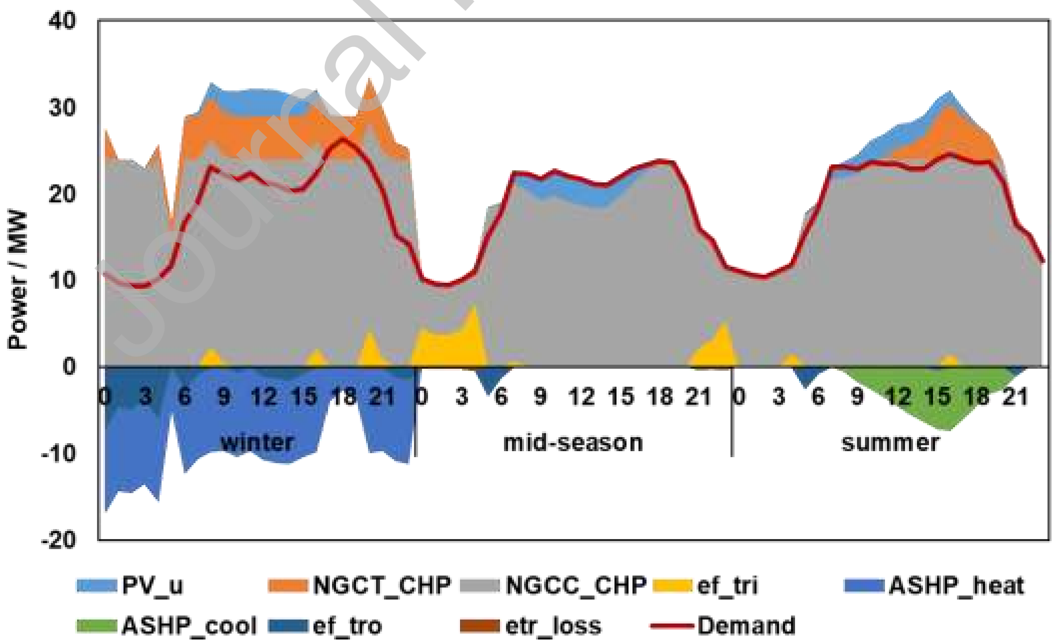


Fig. 9. Hourly power balance in region 1, design point B

4.3 Deterministic and stochastic programming

Previous results are obtained by deterministic optimization. However, ignoring uncertainties rooted in renewable generations might lead to sub-optimal solutions. In this work, uncertainties of PV and WT outputs are characterized in a simple way. The output of PV in each representative day is assumed to follow a two-point distribution. PV might operate at a lower output with a probability of 0.2, or a higher output with a probability of 0.8 in each typical day. Similar settings are applied to WT, as shown in Fig. 10. Thus, $2^3 \times 2^3 = 64$ scenarios are generated.

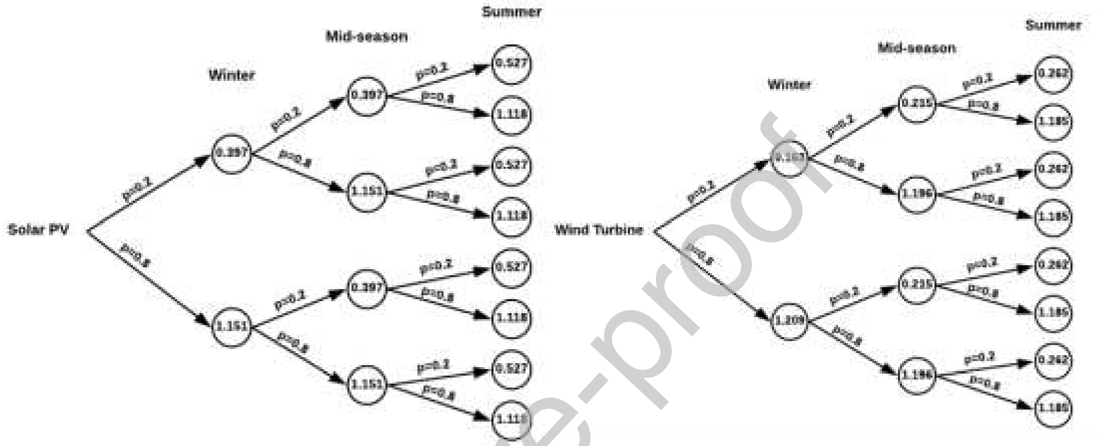


Fig. 10. Scenarios of PV and WT output

Two-stage stochastic optimization is implemented in region 1. The cross-regional energy transfer and carbon emission constraints of stochastic and deterministic schemes are the same. Fig. 11 illustrates the technology configurations of deterministic and stochastic solutions. Compared to the deterministic solution, the stochastic solution requires an additional 5 MW NGCT_CHP, 3.3 MW ASHP, and 1 MW Battery. The total system cost of region 1 varies between 16.10 and 16.27 million USD in 64 scenarios. The total cost expectation is 16.14 million USD, which is 5 % higher than the cost of the deterministic solution.

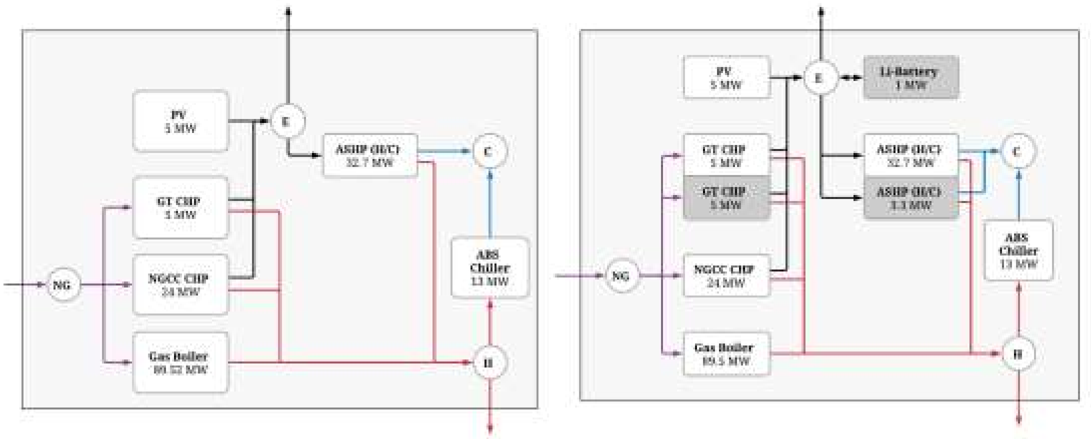


Fig. 11. The deterministic (left) and stochastic (right) technology configurations of region 1, design point B

5 Conclusions

The generic model for the optimal design of integrated urban energy systems under uncertainty and sustainability requirements is presented in this paper. Energy systems engineering methods such as superstructure-based modeling, mixed-integer linear programming, multi-objective optimization, and stochastic programming are integrated into the model. The model equation represents the general relationship between energy and technology, and indices represent the specific energy technology options. Thus, the model itself has universality and can be extended to different urban areas.

The case study results show that conflicting interests exist between economic and environmental performance, and even between different environmental indicators. As carbon constraints tighten, the system's total cost increases, but water consumption decreases first and then increases. The decision-makers can choose the appropriate design point from the Pareto Front of multiple criteria.

The solutions for design and operation plans reveal the significance of the system integration trend. In the design stage, energy networks are built, which enables cross-region energy flow. Both centralized and distributed energy supply exists in the system. The demand and supply balance is satisfied by multi-energy complementary, multi-regional interconnection, and process integration in the operating stage.

Once renewable generation technologies such as PV and WT are deployed, resource availability uncertainties should be considered. Compared to the deterministic solution, the stochastic solution requires more energy generation, conversion, and storage capacity to be installed. The expectation of system cost in region 1 is 5 % higher than the deterministic system cost. Ignoring uncertainties might lead to sub-optimal design.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

CRediT authorship contribution statement

Zhihao Chen: Methodology, Formal analysis, Writing – original draft. **Styliani Avraamidou:** Methodology. **Pei Liu:** Conceptualization, Writing – review & editing. **Zheng Li:** Investigation. **Weidou Ni:** Supervision. **Efstratios N. Pistikopoulos:** Methodology.

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Appendix A. Nomenclatures

Table A.1. Parameters of the model

Symbol	Definition
AREA	Area of the region
CEI	Carbon emission intensity
DAYS	The number of days in a specific season
DIST	Distance between the two regions
DMD	Energy demand in each time step
DURATION	The duration of a full charge/discharge
FP	Fuel price
IMP	Limit of import energy flow
LAND	Land use of unit technology capacity
LINK	Whether networks are allowed to be built between the two regions
LOL	Lower operating level of technologies
M	A big number

NUM	The number of energy import gate station
PERCENT	Percentage of the area of a region that can be allocated to certain technology
RA	Renewable availability (maximum load factor)
SCAP	Single unit's capacity
WATER	Water consumption of unit technology output
ΔH	The duration of a time step
η	Efficiency

Table A.2. Continuous variables of the model

Symbol	Definition
ac	Annual cost
atc	Annual total cost
ate	Annual total emission
atw	Annual total water consumption
ef	Energy flow
ic	Installed capacity
str	Energy stored in the storage facility
tc	Total cost throughout the planning horizon
te	Total emission throughout the planning horizon
tw	Total water consumption throughout the planning horizon

Table A.3. Integer variables of the model

Symbol	Definition
b	Binary variable
iu	The number of installed units
ou	The number of operating units

Table A.4. Indices of the model

Symbol	Definition
e	Energy
pe (e)[1]	Primary energy
re (pe)	Renewable energy
nre (pe)	Non-renewable energy
se (e)	Secondary energy
t	Technology
gnt (t)	Generation technology
rgt (gnt)	Renewable generation technology
chp (gnt)	Combined heat and power (CHP)
nnt (gnt)	Generation technology, neither renewable generation nor CHP
ccs (gnt)	Carbon capture and storage technology
cvt (t)	Conversion technology
stt (t)	Storage technology
n	Networks

y	Year
s	Season
h	Hour
r	Region

1. The expression pe (e) means that primary energy is a subset of energy.

Table A.5. Superscripts of the model

Symbol	Definition
capex	Capital expenditure
cvt_in	Energy flows into a conversion technology
cvt_out	Energy flows out of a conversion technology
exist	Capacity exists in a certain year
fuel	Fuel
gnt_in	Energy flows into a generation technology
gnt_out	Energy flows out of a generation technology
imp	Import
new	New built capacity or unit
off	Off-state
om	Operating and maintenance
on	On state
onsite	Onsite
self-discharge	Self-discharging of storage technology
shut_down	Shut down of technology
start_up	Start-up of technology
stt_charge	Charging of storage technology
stt_discharge	Discharging of storage technology
tr	Energy transmission
upper	Upper bound

Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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