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**Performance prediction and evaluation on the first Balanced Energy Networks (BEN) Part I: BEN and building internal factors**

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**Abstract**

Approximately half of all energy consumed is used for generating heat and hot water in the UK, meanwhile, space heating and hot water consist of about 21% of greenhouse gas emissions. One pathway of decarbonizing heat is electrification of heat, the requirement of electricity is then met through smart grid and demand side response management. A new method for electrifying heat through a balanced energy network (BEN) system, which is situated in central campus of London South Bank University, has been presented. The validations of BEN model are performed against historic measurement data and manufacturer performance data. BEN system performance is then predicted and evaluated through investigating the effects of BEN and building internal factors including system operation mode, thermal storage, indoor set-point temperature, and COP of heat pump. Several key results were drawn as follows: (1) Carbon emissions from building energy consumption mainly depend on operation mode and thermal storage capacity of BEN system, actual heat demand in buildings and carbon emission factor as a function of time; (2) Energy consumption and costs and its carbon emissions will nonlinearly increase with the increasing of indoor set-point temperature ; (3) In January (the coldest month of the year), the heating consumption for operating BEN system will be decreased by 77.9%/72.9% compared with historic monitoring data of 2014/2015; (4) For BEN system, the usage, costs and carbon emissions of electricity supplying to heat pump is an decreasing function of COP.

**Keywords**

Balanced Energy Networks; Electricity Price; Heat Pump; Modelling; Electrification of Heat; Carbon Emissions

Main body

1. **Introduction**

The Paris Agreement’s aim is to significantly shrink the effects and risks from climate change and to handle greenhouse gas emissions mitigation and adaptation. It will then put enormous pressure on the reductions of high-energy consumption in ageing existing buildings [1-5], since approximately half of all energy consumed is used for generating heat and hot water in the UK [6], meanwhile, space heating and hot water consist of about 21% of carbon emissions [7]. The Climate Change Act recently commits the UK government by law to significantly decreasing UK greenhouse gas emissions by at least 100% (compared with 1990 levels) by 2050 [8]. One possible pathway to decarbonize heating is electrification of heat, and the requirement of electricity is then met through a smart and green grid and demand side response (DSR) strategy. Heat pump within energy networks is a key technology and more efficient for delivering electrification of space and water heating than the case for without heat pump. The UK Department for Business, Energy and Industrial Strategy (BEIS) has set a goal of seeing around 14-20% of the UK’s growing space and water heating requirement delivered via heat networks by 2030 and approximately 43% by 2050 [9-11]. However, the amount of heat supplied to buildings in the UK via heat networks is approximately 2% of domestic, public sector and commercial heat demand [9], which is far less than 61% in Denmark.

Currently, there are few practical projects of energy networks and electrifying heat in the UK, although the advantages for heat pump incorporated in energy networks were well investigated theoretically and numerically [12-13]. However, EU countries such as Denmark and the Netherlands have stayed ahead of the UK in applying some novel approaches, e.g., heat pumps, aquifer thermal energy storage (ATES) and waster heat recovery to promote heat networks performance. Next-generation (i.e., Fifth-generation) district heat networks is an integrating system including with ambient temperature heat distribution circuit (no need for expensive insulation), heat pumps supplying to heating and cooling in buildings, thermal energy storage using DSR strategy (e.g., dynamic pricing; to reduce cost of electricity and reduce carbon emissions at peak times), integration of waste heat opportunities, flexibility to expand the network to meet changes in demand, which is an appearing area of multi-function energy networks [14]. It will have the substantial prospective to enlarge the function of heat networks for low-carbon infrastructure. Therefore, approaches adopted to model the prospective attract increasing academic interest recently.

In the past years, although there have been lots of researches in the modelling and performance evaluation of existing energy networks, it still has an obvious lack knowledge in the feasibility, design, application of next-generation energy networks and its whole system modelling evaluation and performance prediction. Most studies mainly focused on the existing third and fourth-generation heat networks and their performance, whereas there was less attention received on next-generation energy networks. Letellier-Duchesne et al. [15] proposed a novel way for district energy system design in terms of the concept of intelligent energy systems. A modelling workflow was put forward in accordance with a novel Rhinoceros-based plugin combining the city building energy model using the network topology optimization as well as the model of heat generation scenario. Suryanarayana et al. [16] presented a thermal load forecasting for heat networks with deep learning and novel feature selection methods. The proposed model of deep learning has higher accuracy, compared with other linear models using automated feature selection. Kauko et al. [17] used the dynamic modelling to investigate technical, energetic and environmental influences from prosumers – customers, both of whom generate and consume heat, in Norway low-temperature districting heating network. The simulation results showed that up to 25% reduction in the building energy demand, via utilization of the surplus heat from a data center, could be achieved compared with a high-temperature reference case. Vandermeulen et al. [18] compared manual and thermostat control strategies with the novel theoretical reference, the upper boundary in term of performance for bypass controllers could be provided. Bypass control could compromise between efficiency and the service quality. Cai et al. [19] introduced a practical evaluation of electrical heating boosters, which are the heat boosting devices using supplementary electric heaters, in the low energy areas. While supplying temperature was decreased from 70 oC to 50 oC, losses of district heat network (DHN) could be decreased by 35%, however, peak power of a low-voltage network would be rised by around 2% with heat booster. Zuehlsdorf et al. [20] demonstrated the booster heat pumps incorporated into the ultra-low-temperature district heat network having the 40 oC forward temperature for generating domestic hot water, via the forward stream heating section to 60 oC, whereas cooling the rest part to 25 oC for the return temperature. Best et al. [21] illustrated an ultra-low-temperature district heat (supply/return temperature: approximately 40 oC/25 oC) in Germany could ensure significant improvement for the efficiency of heat distribution, suitable conditions integrating renewable heat and have no economic disadvantages compared with low temperature district heat (supply/return temperature: approximately 70 oC/40 oC). It could be found heat loss due to large temperature difference between ambient and the above supply/return temperature still would occur. However, the next generation (Fifth-generation) district heat networks with ambient ground temperature heat distribution circuit would significantly avoid heat loss during the heat transport.

 In addition, there have been several studies concentrating on district heat networks and energy systems optimization algorithms. Prina et al. [22] developed EPLANopt model with multi-objective evolutionary optimization algorithm from Python library DEAP coupled to deterministic EnergyPLAN software. The objective functions based on the test case of the South Tyrol, Italy include total annual costs, CO2 emissions and renewables percentage with the system. It will reduce the carbon emissions by 44% if increasing energy efficiency in buildings and PV capacity installed whereas maintaining the whole annual costs for the reference scenario. Vesterlund et al. [23] conducted an operation optimization for multi-source complicated district heat networks considering comprehensive feature for pressure and heat losses through the pipelines. He has developed an evolutionary mixed integer linear programming (MILP) algorithm and coupled to the heat network. Simulation results of Matlab/Simulink model adopting the proposed algorithm illustrated thermal losses costs are more significant than pumping power cost. Gong et al. [24] proposed the complex district heat system in order to decrease system pressure level. Two simulation cases have been investigated based on different operation control strategies. The simulation results showed the optimal pressure control method could ensure more stable operating levels for distributed pumps and could save around 57% pump energy while the flow rate is 0.3 1/h. Ayele et al. [25] developed the integrated optimizing strategy in order to overcome the restriction, i.e., the compromise between optimal sizing and placement of heat pump of heat network perspective and electricity grid. The results indicated optimizing placement and sizing of heat pumps and a heat only boiler with the proposed methodology could avoid the unacceptable voltage profiles and electricity grid overloading. It can save approximately 41.2% for electricity loss and around 5% of total operation cost. Jie et al. [26] proposed four different kinds of strategies to achieve the minimum heat loss costs and pumping costs with an operation optimizing model by Matlab. It has been concluded both heating parameters and operation method would influence the optimal results in an existing district heating system. Morvaj et al. [27] developed an optimizing design, distributed energy system operating, and the optimizing layouts for heat network. The comprehensive multi-objective MILP model of city-scale energy systems was proposed. The results illustrated the developed district heating system would reduce emissions 23% compared with the reference scenario in term of the same costs. Zhang et al. [28] developed the model of large-scale incorporated energy systems and investigated the multi-objective optimizing approach, i.e., Multi-objective group searching optimizer using adaptive covariance and levy flights (MoGSO-ACL). Through comparing with group searching optimizer using multiple producers (GSOMP), MoGSO-ACL is more efficient in looking for better Pareto-optimal solutions considering diversity and convergence.

Based on the abovementioned research, it could be obviously seen that many studies paid close attention to the conventional heat networks, individual energy systems modelling and their performance optimization. But, less attention was received for the whole energy network modelling of next-generation energy network, particularly an integrated system, e.g., BEN system. This paper is aiming to study the feasibility of next-generation energy networks and modelling of its integrated whole system, considering renewables technologies, DSR strategy and cold water heat network (CWHN or called ambient ground temperature heat distribution circuit) linking two different buildings. In addition, this research will predict and evaluate system performance of proposed BEN in terms of real system operations.

 This article presents some results from the model built using energy system software TRNSYS to indicate a new built BEN system in London South Bank University (LSBU). TRNSYS was already used as the popular simulation software to model the energy systems, evaluate and predict their performance in several studies [29-32]. Sartor et al. [29] built the heat transfer modelling for district heating networks and utilized the classical TRNSYS Type 31 component according to a Lagrangian method to model a pipe and duct. Safa et al. [30] employed Type 668 GSHP module to investigate cooling and heating performance based on building loads and source temperatures. Renaldi and Friedrich [31] developed the validated TRNSYS model for Drake Landing Solar Community with publicly possible data and techno-economically analyzed the solar district heat with the seasonal heat storage in the UK. Flynn and Siren [32] created a model of the community for the solar district heat system facilitated with borehole seasonal heat storage via TRNSYS and simulations were performed in 5 different cities: Helsinki, Hohhot, Dublin, Oviedo and Perpignan.

BEN was retrofitted to two university buildings, i.e., T-block and J-block in central London, containing a CWHN, linked two borehole wells in London aquifers and electrifying heat, i.e., heat pumps as well as smart thermal storage with DSR strategy. The objectives in this paper include as follows: (1) building a system model of BEN numerically with Energy System Simulation package TRNSYS considering a real-world BEN; (2) predicting and evaluating performance of whole BEN system based on internal factors of BEN and buildings; (3) providing possible guidelines for the similar BEN system design and optimization, e.g., thermal storage capacity, system operation modes and COP of heat pump etc.

 The article mainly includes as follows: BEN project and its system model are introduced and analyzed. Following that, BEN system model validations are performed against measurement data and manufacturer performance data. Then, BEN system performance will be predicted and evaluated through numerically investigating the effects of BEN and building internal factors including system operation mode, thermal storage, indoor set-point temperature, and COP of heat pump. Subsequently, some discussions and limitations will be presented. Finally, some key results will be concluded and future work will be proposed.

1. **Description of BEN project**

 The BEN is a demonstration project of the integrated energy systems situated in LSBU located in a dense urban environment - central London (see Fig. 1(a)). BEN has been designed to integrate district heat networks with smart and green grid technologies to balance heat and electricity generation delivery via an optimal method, which can minimize energy, costs and greenhouse gas emissions. It created considering principles of aquifer thermal energy storage (ATES) to build the first cold water heat networks (CWHN) worldwide [33] for application in district heat in the UK.

Main principle behind BEN is electrification of heat when minimizing influences on peak electrical loads with a new integration of measures. BEN system connects a Tower Block and a J-Block (Fig. 1(b) and (c)) with two approximately 110 m boreholes having the rated electrical power 22 kW, and they could deliver underground water of London aquifer in the range of about 13 oC – 15 oC [33-34]. Transported by the cold water heat network (CWHN) along Kell Street, London, the borehole system can provide the heat sink source for reversible heat pumps having the maximum electrical power 95 kW. Water temperature in CWHW could be increased by heat rejection, which could in turn enhance COP of heat pumps in the heating mode. Global system performance could still be enhanced by transfering loads to off-peak times via a combination of distributed smart Mixergy heat storage with 10 kL capacity and DSR strategy. Whereas those advanced technologies were all proven separately, BEN is the first known heat networks worldwide to integrate the above components all into one balanced system.



(a)



(b)



(c)

Fig. 1(a): Layout of T-Block, cold water heat network (CWHN), 2 boreholes and J-Block at LSBU (background from [35]) (a), BEN system schematic diagram (b) and its components (c).

1. **Model methodology**
	1. **Simulation setups**

 The simulated BEN system consists of all components for the real condition in LSBU. Internal factors of BEN system (thermal storage, heat pump COP) and its integrating two buildings (indoor set-point temperature) have been investigated considering energy consumption, costs and CO2 emissions for different cases.

* 1. **Lists of assumptions**

 The simulation is an elementary analysis and prediction of expected performance of BEN in LSBU. The assumptions set are in line with previously applied in those physical models of energy networks [36-37] and HVACs [38-40]:

* T-Block and J-Block have uniform temperature and heating;
* The effect of relative humidity on building thermal losses is ignored;
* Thermal losses of hot water from thermal storage/heat pump to buildings are neglected;
* The steady state hydraulic situation within BEN system is contemplated;
* The Fluids within BEN system are considered as ideal;
* Thermal diffusion, hydraulic dispersion and axial heat transmission among water pipelines within BEN system are ignored;
* Thermal storage for pipeline insulation and the ground are neglected.

Two university buildings – T-Block and J-Block – are intensely heat dominated, although BEN system is designed to meet heating and cooling requirements.

* 1. **Methodology**

Energy system simulation (ESS) methodology was applied to predict and evaluate BEN system performance. The popular ESS simulation tool is TRNSYS (Transient system simulation program) [41], which is based on the network model and has been employed in this study. The program can dynamically identify the significant parameters of energy systems, building energy performance and thermal environment. Detailed simulation parameter settings are indicated in Table 1. The whole TRNSYS model diagram for BEN is demonstrated in Fig. 2, which includes ground-source heat pump, hot water tank, buildings etc. and will be investigated in detail in section 4.

**3.3.1 *Benchmark Modelling***

It is necessary to set a benchmark case for the simulation investigation of BEN system performance. The main settings for the benchmark include 1) the indoor temperature set-point is (16 + 5\*Workday) oC, i.e., 21 oC from 8 am to 6 pm on workdays and 16 oC for the other situations; 2) air change rate is 1.6 h-1; 3) heat pump COP is 3.15.



Fig. 2: Whole TRNSYS model schematic diagram for BEN

Table 1: Main components and parameter settings (default condition).

|  |  |
| --- | --- |
| Name | Main parameters |
| Borehole | Reference borehole flow rate: 20 L/s; Outlet temperature: 14 oC |
| Heat pump | Specific heat of water: 4.19 kJ/kgK; Rated heating capacity: 300 kW, Rated electricity power: 95 kW, Reference COP: 3.15 |
| Loads | Specific heat of heat: 4.19 kJ/kgK; Inlet flow rate: 20 L/s |
| Hot water tank (from Mixergy Ltd.) | Volume: 10 kL, Rated heating capacity: 300 kW (design power) when the temperature difference between inlet and outlet is 25 oC |
| Heat exchanger | Specific heat of water: 4.19 kJ/kgK; efficiency: 0.9  |
| T-Block [33-34] | Total floor area: 9076.37 m2; Volume: 27229.1 m3; Air exchange rate: 1.6 h-1 (benchmark); Indoor temperature set-point: 5\*Workday + 16 oC (benchmark); Average U-value: 0.3 W/m2K  |
| J-Block [33-34] | Total floor area: 10610 m2; 31830 m3; Air exchange rate: 1.6 h-1 (benchmark); Indoor temperature set-point: 5\*Workday + 16 oC (benchmark); Average U-value: 0.3 W/m2K  |
| Weather condition | TMY2 data for London [42] |

**3.3.2 Model logic and equations**

Two university buildings (T-Block and J-Block) are modeled as the thermal stores in this study. The heating energy (hot water) for two buildings is supplied by natural gas boiler in previous heating system (before renovation). For BEN system (the scenario of after renovation), the heating energy is firstly provided by water source heat pump when the heating demand is smaller than 300 kW; the gas boiler-based heating system will supply the rest heating requirement if heating demand is larger than 300 kW. In addition, thermal storage (Mixergy hot water) tank, which is charged during the midnight (i.e. its electricity price is cheaper than other period of time), could supply the heating energy from 4 pm to 7 pm (peak time for electricity usage). Electricity prices dynamically change from day to night as a function of time, according to diverse distribution network operator (DNO), i.e., distribution use of system (DUoS) charges scheme (dynamic pricing) outlined in London Power Networks (LPN) schedule of price [43]. Table 2 illustrates LPN charge schedule for DUoS applied in the next simulation sections. Equ (1) shows the heating requirement of the building supplied by BEN system. For the gas boiler-based heating system, the gas usage for heating energy is defined by Equ (2). The heating energy supplied by heat pump and Mixergy tank are indicated by Equs (3) and (4), respectively. The heat pump COP is expressed by amount of heating (heating capacity Cheat) moved per unit of input work (power draw Pheat) required as shown in Equ (5).

$\sum\_{i=1}^{n}Q\_{heatj}=\sum\_{i=1}^{n}Q\_{gasj}+\sum\_{i=1}^{n}Q\_{hpheatj}+\sum\_{i=1}^{n}Q\_{tankheatj}$ (1)

$Q\_{gasj}=µ\*Q\_{gasrealj}$(2)

$Q\_{hpheatj}=Q\_{hpelej}\*COP\_{j}$(3)

$Q\_{tankheatj}=Q\_{hpeletankj}\*COP\_{j}$(4)

$COP= \frac{C\_{heat}}{P\_{heat}}$(5)

where Qheat is the heat demand of building in kWh, Qgas is the gas usage for heating in kWh, Qhpheat is the heating from heat pump in kWh, Qtankheat is the heating from tank storage in kWh, Qgasreal is the actual gas usage in kWh, Qhpele is the electricity usage for heat pump in kWh, COP is heat pump coefficient of performance, Qhpeletank is electricity usage from heat pump for hot water storage in kWh, i is the time in hour, j is 1, 2 representing building 1 and 2, µ is gas boiler efficiency and set as 0.9.

Table 2: BEN electricity pricing scheme [43]

|  |  |
| --- | --- |
| Band Price (p/kWh) | Time period |
| Green: 0.005 | 0:00 – 7:00 |
| Yellow: 0.221 | 7:00 – 11:00 |
| Red: 4.367 | 11:00 - 14:00  |
| Yellow: 0.221 | 14:00 – 16:00 |
| Red: 4.367 | 16:00 – 19:00 |
| Yellow: 0.221 | 19:00 - 23:00 |
| Green: 0.005 | 23:00 – 24:00 |

* 1. **Model validation**

It is necessary to validate the model using TRNSYS before it will be broadly used in this work, although current numerical program was successfully applied in many studies [38, 44-47]. The validations were completed via compared simulation results with measurement data and manufactory performance data (including inlet and outlet temperatures and flow rates etc. for source and load sides of heat pump). Parameters that identify T-Block and J-Block containing their total floor area, volume, air change rate and average u-value listed in Table 1.

TRNSYS simulation model has been first validated via simulating past performance of T-Block’s natural gas boiler-based heating system. Simulations were operated using gas boilers as heat sources to two university buildings, replacing for BEN. Output of simulations heating consumption was compared with historic collected data records from monitoring. The heat is conveyed to the water in boilers and is then passed on to ­­T-Block by pipes and radiators.

The historic measuring data has been collected within the course of 2nd and 3rd weeks of January, 2015 and 2017. Comparison of simulated heating consumption for T-Block to real gas consumption values yields the errors of 0.25% and 5.76%, respectively, based on Table 3, i.e., the abovementioned results are in very good agreement with each other. It will then suggest the proposed model is functional and it can guarantee the reliability of following simulation studies.

Table 3: Comparison of heating consumption between historic data and simulation results

|  |  |  |
| --- | --- | --- |
| Historic data | Real Qgasreal in kWh | Consider efficiency 0.9 of boiler in kWh |
| 2nd and 3rd weeks Jan 2015 | 92100.70 | 82890.63 |
| 2nd and 3rd weeks Jan 2017 | 97483.25 | 87734.93 |
| Simulation result | - | 82680.6 |
| Error for 2015 | - | 0.25% |
| Error for 2017 | - | 5.76% |

BEN system simulation model based on the same settings of manufacturer performance data has been validated via comparing the simulated heat pump performance with the manufacturer’s performance data (PD) at 70 oC (Leaving load temperature: LLT) and 80 oC (LLT) conditions, both of which are dominant real operating heat modes, with COP values of 3.15 (Entering source temperature (EST): 15 oC), and 2.74 (EST: 15 oC) and 3.03 (EST: 10 oC), 2.59 (EST: 10 oC), illustrated by Table 4.

This simulation model based on the same settings of manufacturer performance data (including inlet and outlet temperatures and flow rates etc. for source and load sides of heat pump) obtains results of the aforementioned at COPs of 2.717 (EST/LLT: 15/80 oC), 3.12 (15/70 oC) and 2.52 (10/80 oC), 2.86 (10/70 oC). It is quite close to the manufacturer’s rated COPs of 2.74 (15/80 oC), 3.15 (15/70 oC) and 2.59 (10/80 oC), 3.03 (10/70 oC), respectively. Their maximal discrepancy between simulation results and actual COPs is 5.61%. Those results seen from Table 4 are in a very reasonable agreement.

Table 4: Comparison of COP from model results with PD from heat pump manufacturer

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Type | EST (oC) | ELT (oC) | LLT (oC) | COP of PD | COP of model | Discrepancy |
| 1 | 15 | 60 | 70 | 3.15 | 3.12 | 0.95% |
| 2 | 15 | 70 | 80 | 2.74 | 2.717 | 0.84% |
| 3 | 10 | 60 | 70 | 3.03 | 2.86 | 5.61% |
| 4 | 10 | 70 | 80 | 2.59 | 2.52 | 2.61% |

These two corroborative tests give us confidence to proceed to use our model to evaluate and predict building heating energy consumption and BEN system performance including heat pump and hot water storage as well as system costs and carbon emissions.

1. **Results and findings**
	1. **Benchmark mode and effect of thermal storage for BEN system**

 In order to evaluate BEN system (the scenario of after renovation, which is different from the scenario of old heating system, i.e., only having natural gas boiler system) performance and analyze the effect of thermal storage, three modes as different simulation cases have been investigated, as illustrated in Table 5, which represent three operating modes of BEN (after renovation), i.e., a) heat pump is operating all the day (Mode 1: Benchmark 1), b) heat pump is operating all the day except 4 pm to 7 pm using real Mixergy tank, where hot water is heated by heat pump during midnight with a cheapest electricity price, which is also one of real demand side response (DSR) strategy (Mode 2: Benchmark 2), and c) heat pump operating all the day except 4 pm to 7 pm using 4 times Mixergy tank volume (Mode 3). The volume of existing Mixergy tank is 10 kL, which could supply hot water of around 300 kWh while a temperature difference between an inlet and outlet of tank is 25 oC, which is based on the manufacturer data and design, i.e.,Mixergy tank is a smart thermal storage, which has an advanced controller to maintain the temperature difference between inlet and outlet in the hot water tank all the time; in addition, there is a high-quality thermal insulation for the smart hot water tank. Also, in order to simplify the model, thus, its power output is considered as a constant in this study.

The natural gas and electricity price in London are averagely 3 p/kWh [48] and variable based on Table 2, respectively. The gas and electricity carbonequivalent emission factors in the UK are 0.18416 kg/kWh (constant) [49] and variable as a function of time [50], respectively.

Table 5: Operation mode simulation settings for Mixergy® tank

|  |  |  |
| --- | --- | --- |
|  | Heat pump | Mixergy tank  |
| Mode 1 (Benchmark 1) | All day operating | Not operating |
| Mode 2 (Benchmark 2) | All day operating except 4 pm to 7 pm | Operating from 4 pm to 7 pm with real Mixergy capacity |
| Mode 3 | Same as Mode 2 | Same as Mode 2 |

 As shown in Table 6, annual electricity consumption 155.25 MWh for heat pump operating Mode 2 and Mode 3 is the same due to the same energy supply mode, i.e., Mixergy tank instead of heat pump is running during 4 pm to 7 pm. Annual gas consumption (for T-Block heating: Qgas1) 136.11 MWh in Mode 2 is higher than Mode 1 100.66 MWh for T-Block. That is because, for Mode 1, heat pump could supply maximal capacity 300 kW to building from 4 pm to 7 pm, if building heating demand is higher than 300 kW per hour, natural gas will be consumed. However, for Mode 2, from 4 pm to 7 pm, Mixergy tank can provide just maximal heating energy 300 kW in all. Once exceeding 300 kWh, building will consume natural gas. However, due to Mode 3 with 4 times Mixergy capacity supplying heating energy from 4 pm to 7 pm, annual gas consumption of Mode 3 is 91.27 MWh, which is obviously lower than Modes 1 and 2. Considering the total annual energy consumption Qta, Mode 3 is consuming 271.62 MWh, which is low than Mode 1: 283.15 MWh by 4.24% and Mode 2: 303.65 MWh by 11.8% , respectively. Similar to total annual energy consumption, Mode 3 has the lowest total costs Ct 3004 £and carbon emissions Et 52.26 t compared with Mode 1: 5654 £and Mode 2: 5627 £; Mode 1: 56.3 t and Mode 2: 58.2 t. Based on the above results, it could be then concluded Mode 3 is an optimal operation mode for BEN system, from energy consumption, costs and carbon emission points of view.

Table 6: Comparisons of energy demand, costs and carbon emissions for different modes in Building 1

|  |  |  |  |
| --- | --- | --- | --- |
| Baseline of Building 1 | Mode 1 | Mode 2 | Mode 3 |
| Qhpele1 kWh | 182493.94 | 155253.63 | 155253.63 |
| Qtanke1 kWh |  | 12289.62 | 25099.59 |
| Qgasreal1 kWh | 100659.52 | 136106.6 | 91271.77 |
| QtakWh | 283153.46 | 303649.85 | 271624.99 |
| Cgridhp1 £ | 2634.19 | 1543.604 | 1543.604 |
| Cgridtank1£ |  | 0.614 | 1.255 |
| Cgas1£ | 3019.786 | 4083.199 | 1459.116 |
| Ct£ | 5653.976 | 5627.417 | 3003.975 |
| Eelechp1kg | 37785.71 | 30913.06 | 30913.06 |
| Eelectank1kg |  | 2224.422 | 4543.025 |
| Egas1kg | 18537.46 | 25065.4 | 16808.61 |
| Etkg | 56323.17 | 58202.882 | 52264.695 |

Table 7 illustrates monthly peak value for gas consumption under Mode 1, its appearing time and total monthly gas consumption for T-block and J-block. Compared with all peak values, the maximal gas consumption 449.8 kW (T-block) and 568.7 kW (J-Block) appear in the morning at 10 am (T-block) and 9 am (J-block) on January 13th for both buildings. It means January is the coldest month of the year in London, which could be verified by the total gas consumption of January with maximal values 19.9 MWh (T-block) and 43.7 MWh (J-block), respectively.

 Table 7: Monthly peak value, its peak hour and total usage for gas consumption in under Mode 1

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | **T-block Peak Qgasreal1 (kWh)** | **Total (kWh/month)** | **J-Block Peak Qgasreal2 (kWh)** | **Total (kWh/month)** |
| **Jan** | 449.8169; 13th 10am | 1.9909e+04 | 568.6838; 13th 9am | 4.3698e+04 |
| **Feb** | 370.8092; 4th 10am | 1.7353e+04 | 469.7970; 10th 9am | 4.0834e+04 |
| **Mar** | 379.0125; 10th 10am | 1.4339e+04 | 462.0149; 10th 10am | 3.0873e+04 |
| **Apr** | 362.8852; 21st 10am | 9.8151e+03 | 435.4312; 21st 10am | 2.0667e+04 |
| **May** | 293.7867; 12th 10am | 3.8504e+03 | 348.0154; 12th 10am | 7.8672e+03 |
| **Jun** | n/a | 211.6259 | n/a | 767.3025 |
| **Jul****Aug** | n/an/a | 00 | n/an/a | 59.85240 |
| **Sep** | 13.0727; 30th 9am | 34.4442 | 59.8024; 30th 9am | 459.6924 |
| **Oct** | 286.9290; 28th 10am | 4.3990e+03 | 369.2025; 28th 10am | 8.4229e+03 |
| **Nov** | 331.9205; 24th 10am | 1.1801e+04 | 439.4788; 4th 9am | 2.4537e+04 |
| **Dec** | 381.0000; 2nd 10am | 1.8946e+04 | 487.9431; 23rd 9am | 4.1258e+04 |

 Fig. 3 illustrates the number of hours for the peak value of different energy consumption above (i.e., Qheat and Qgasreal: peak) or equal (i.e., Qhpheat: peak) to 300 kWh in T-Block (a) and J-Block (b) under Mode 1, Mode 2 and Mode 3. It could be seen from Fig. 3 the maximal heating demand peak times take place in December (110 hours, which means how many hours the maximal heating demand peak appears) and January (220 hours) for T-Block and J-Block, respectively. Compared with Mode 1, hour amounts for the peak value of actual gas usage Qgasreal12 and Qgasreal22 under Mode 2 are higher, however, the hour amounts for the peak value of heating supplied by heat pump Qhpheat12 and Qhpheat22 under Mode 2 are lower. The main reason is that, for Mode 1, heat pump still supplies the heating energy for both buildings from 4 pm to 7 pm, i.e. the hour amounts of heating energy supplied by heat pump is higher than Mode 2 and 3. Thus, the hour amounts for the peak value of actual gas usage will be decreasing compared with Mode 2. But, the interesting result is that, for Mode 3, the hour number for the peak value of actual gas usage is lower than Mode 2 and similar to Mode 1. The possible cause is the Mixergy tank capacity of Mode 3 is four times more than Mode 2, which could supply enough hot water to meet Qheat from 4 pm to 7 pm. Then, it doesn’t need further natural gas to supply the heating for both buildings.

(a)

(b)

Fig.3: Number of hours for the peak value of energy above (Qheat, Qgasreal: peak) or equal (Qhpheat: peak) to 300 kWh in T-Block (a) and J-Block (b) under Mode 1, Mode 2 and Mode 3. Qheat1,2 is heat demand of building 1 or 2, Qgasrealij is actual gas usage for building i and Mode j, Qhpheatij is heating supplied by heat pump for building i and Mode j.

Fig. 4 indicates monthly total costs for grid supplying to heat pump and Mixergy tank, and natural gas in Building 1 under 3 different Modes. Compared with Mode 1, gas costs, for example, in January could be decreased by 72.5% for Mode 2 (Table 8). However, compared with Mode 3, gas costs in January could be increased by 58.3% for Mode 2 (Table 8). The aforementioned results could illustrate that the distribution use of system prices scheme for Mixergy tank within BEN system takes effect on reducing energy costs. In addition, the bigger capacity Mixergy tank has, the lower costs the energy has. It also depends on the actual heat demand of building. Meanwhile, considering electricity costs from the heat pump in January, for Mode 2, it will be decreased by 42.3% compared with Mode 1 (Table 8). In other words, the heating energy for buildings during 4 pm to 7 pm (peak time) is supplied by the Mixergy tank, where the heating energy (hot water) was produced with the cheaper electricity during midnight. Electricity costs from the heat pump for Mode 3 are identical to Mode 2. It is due to the fact that the operating time (except 4 pm to 7 pm) for both Modes is the same and the actual heat demand of buildings is the same. The sole difference in between is the capacity of Mixergy tank, which will results in the different electricity costs from Mixergy tank e.g. 10.1 £ (Mode 2) and 20.3 £ (Mode 3) in January, respectively; and the different gas costs 75800 £ and 31600 £, respectively.

Table 8: Comparison of gas and electricity costs in January for building 1

|  |  |  |  |
| --- | --- | --- | --- |
| Type | Mode 1 | Mode 2 | Mode 3 |
| Gas costs in £ | 276000 | 75800 | 31600 |
| Electricity in £  | 40200 | 23200 | 23200 |

In contrary, for Building 2, the monthly costs for grid are always higher than gas costs under Mode 1, seen from Fig. 5(a). The main reason may be the heating demand of Building 2 is larger than Building 1 and lies mainly in the range of near around 300 kWh, which will result in that heat pump always supplies heating energy under the maximal heating power. However, compared with Mode 1, the total monthly costs (gas plus grid costs), for example, in January will be decreased by 60.3% for Mode 2 (Table 9). Meanwhile, compared with Mode 3, the total monthly costs in January could be increased by 8.70% for Mode 2 (Table 9). The effect of Mixergy tank capacity due to dynamic pricing on costs for Building 2 is not obvious. It corresponds to the conclusion as mentioned before, i.e., the actual heat demand of building is another key factor for costs.

Table 9: Comparison of total costs in January for building 2

|  |  |  |  |
| --- | --- | --- | --- |
| Type | Mode 1 | Mode 2 | Mode 3 |
| Gas + Grid costs in £ | 375000 + 131000 | 33900 + 167000 | 33900 + 123000 |

(a)

(b)

(c)

Fig. 4: Monthly costs for grid and Mixergy tank, and natural gas in Building 1 under Mode 1 (a), Mode 2 (b) and Mode 3 (c). Cgridhp, Cgas and Cgridtank are electricity, actual gas costs & electricity costs for hot water tank.

(a)

(b)

(c)

Fig. 5: Monthly costs for grid and Mixergy tank, and natural gas in Building 2 under Mode 1 (a), Mode 2 (b) and Mode 3 (c). Cgridhp, Cgas and Cgridtank are electricity, actual gas costs & electricity costs for hot water tank.

Fig. 6 illustrates monthly carbon emissions for grid (Eelechp) and Mixergy tank (Eelectank), and natural gas (Egas) in Building 1 and Building 2 under Mode 1 (a), Mode 2 (b) and Mode 3 (c). Similarly to costs, for Building 1, carbon emission from electricity and gas under Mode 2 is lower than Mode 1 around 1070 kg and higher than Mode 1 about 990 kg, respectively, however, the total carbon emission is decreased 80 kg; Compared with Mode 3, carbon emission from gas and heat pump electricity under Mode 2 is higher than Mode 2 approximately 1320 kg and identical to Mode 2, i.e., the reason caused is explained in the part of electricity costs: the operating time (except 4 pm to 7 pm) for both Modes is the same and the actual heat demand of buildings is the same.

For Building 2, carbon emission from heat pump electricity and gas under Mode 2 is lower than Mode 1 about 1800 kg and higher than Mode 1 around 2150 kg, respectively; Compared with Mode 3, carbon emission from gas and heat pump electricity under Mode 2 is higher than Mode 2 around 2640 kg and identical to Mode 2, respectively.

In addition, monthly carbon emissions for Mixergy tank, seen from Fig. 6(b) and (c) are very small due to hot water stored in Mixergy tank with lower carbon factor during midnight [50]. The following is interesting to note based on Fig. 6(b) and (c): carbon emissions for Mixergy tank correlate with and depend on 1) system operation mode, 2) tank volume, 3) actual heat demand of buildings and 4) carbon emission factor as a function of time.

(a-1)

(a-2)

(b-1)

(b-2)

(c-1)

(c-2)

Fig. 6: Monthly carbon emissions for grid and Mixergy tank, and natural gas in Building 1 and Building 2 under Mode 1 (a), Mode 2 (b) and Mode 3 (c). Eelechp, Eelectank and Egas are carbon emissions from electricity usage, electricity usage for hot water tank & actual gas consumption.

 In summary, Mode 3 offers the best performance because it has more thermal storage and allows the building to stay warm without gas or electricity during peak hours (4-7 pm).

* 1. **Effect of indoor set-point temperatures**

Indoor set-point temperatures not only influence indoor thermal comfort but affect energy demand, costs and CO2 emissions, and predicts BEN system performance. The aforementioned boundary conditions are kept excluding set-point indoor temperatures. Three different set-point temperatures (14 + 5\*Workday) oC, (18 + 5\*Workday) oC and (20 + 5\*Workday) oC have been simulated and compared with the benchmark case Mode 2 (real BEN system operation) of (16 + 5\*Workday) oC.

Table 10 shows the comparison of diverse indoor set-point temperatures affecting the BEN system performance and energy demand, costs and CO2 emissions. For both buildings, all energy demand, costs and CO2 emissions obviously increases with indoor set-point temperature. For example, compared with 14 + 5\*Workday, Qhpele1 is increased by approximately 35.3% for 16 + 5\*Workday. However, compared with 18 + 5\*Workday and 20 + 5\*Workday, Qhpele1 is decreased by approximately 41.7% and 87.8% , respectively. Considering the balance between energy and costs saving, carbon emissions reduction and thermal comfort, 16 + 5\*Workday is an optimal set-point among them.

Table 10: Comparison of diverse indoor set-point temperatures in Building 1 (a) and Building 2 (b) affecting BEN system performance and energy demand, costs and CO2 emissions (Mode 2)

(a)

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Baseline of Building 1 | Qhpele1kWh | Qhpeletotank1kWh | Qgasreal1kWh | Cgridhp1£ | Cgridtank1£ | Cgas1£ | Eelechp1kg | Eelectank1kg | Egas1kg |
| 5\*workday+20 oC | 291708.18 | 20119.88 | 260258.8 | 2519.981 | 1.005994 | 7807.765 | 57485.77 | 3641.698 | 47929.27 |
| 5\*workday+18 oC | 220039.56 | 16515.82 | 188647 | 2037.979 | 0.8257909 | 5659.411 | 4354.399 | 2989.363 | 3474.124 |
| 5\*workday+16 oC | 155253.63 | 12289.62 | 136106.6 | 1543.604 | 0.614 | 4083.199 | 30913.06 | 2224.422 | 25065.4 |
| 5\*workday+14 oC | 100472.38 | 8619.1 | 93977.25 | 1104.899 | 0.431 | 2819.317 | 20276.84 | 1560.057 | 17306.85 |

(b)

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Baseline of Building 2  | Qhpele2kWh | Qhpeletotank2kWh | Qgasreal2kWh | Cgridhp2 £ | Cgridtank2 £ | Cgas2£ | Eelechp2 kg | Eelectank2kg | Egas2kg |
| 5\*workday+20 oC | 344856.11 | 25765.03 | 590298.4 | 3666.257 | 1.288251 | 1770.895 | 69136.6 | 4663.47 | 108709.3 |
| 5\*workday+18 oC | 275907.74 | 22816.03 | 426848.9 | 3202.01 | 1.140802 | 12805.47 | 55892.08 | 4129.702 | 78608.5 |
| 5\*workday+16 oC | 210409.38 | 19662.61 | 292494.1 | 2639.079 | 0.9831305 | 8774.823 | 43147.56 | 3558.932 | 53865.72 |
| 5\*workday+14 oC | 151709.78 | 15749.57 | 186954.3 | 2030.573 | 0.7874785 | 5608.628 | 31519.36 | 2850.672 | 34429.5 |

Fig. 7 illustrates historic measured data of gas usage for heating in 2014 and 2015 and simulation results for heating consumption, i.e., gas usage and electricity usage for heat pump. Seen from Fig. 7, the maximal heating consumption is in January for both measured data and simulation results, which just corresponds to the aforementioned conclusion: January is the coldest month of year in London. From June to September, not only measured data but also simulation results of heating consumption approach approximately zero, that is because 1) heating is not completely required due to weather condition; 2) it is the university summer holiday during that period. The simulation results also indicate the heating energy consumption could reduce sharply compared with historic data after BEN system operating. For example, in January, the heating consumption for BEN system will be decreased by 77.9% or 72.9% compared with 2014/2015 (Table 11).

Table 11: Comparison of heating consumption between historic data in January 2014, 2015 and simulation results

|  |  |
| --- | --- |
| Type | Heating consumption in kWh |
| Simulation results | 25280 (gas) + 27111 (electricity) |
| Measured data in 2014 | 237211 |
| Measured data in 2015 | 193215.4 |

Fig. 7: Comparison of historic gas usage data in 2014 (2014 Gas), 2015 (2015 Gas),& BEN benchmark (Mode 2) simulation results of real gas usage (SimGas) and electricity usage (SimEleHP) for Tower Block

Fig. 8 shows the effect of indoor set-point temperature on energy demand (a), costs (b) and carbon emissions (c) for Building 1 under Mode 1. For energy demand, it is shown in Fig. 8 (a-1) to (a-4) for four different temperature settings, all kinds of energy will nonlinearly increase with the increasing of temperature. For example, compared with 14 + 5\*Workday, the gas usage in January is increasing by 29.0% for 16 + 5\*Workday (Table 12). However, the former set-point couldn’t meet thermal comfort in winter [38, 51]. In contrary, compared with 18 + 5\*Workday and 20 + 5\*Workday, the gas usage in January is decreasing by 29.2% and 74.5% for 16 + 5\*Workday (Table 12), respectively. For the electricity in January supplying to heat pump, compared with 14 + 5\*Workday, it will increase by 43.4%; however, compared with 18 + 5\*Workday and 20 + 5\*Workday, it will decrease by 31.4% and 59.4% for 16 + 5\*Workday (Table 12), respectively.

Table 12: Comparison of gas and electricity usage in January among different set-points

|  |  |  |
| --- | --- | --- |
| Type | Gas usage in kWh | Electricity usage in kWh |
| 14 + 5\*Workday | 19600 | 18900 |
| 16 + 5\*Workday | 25280 | 27100 |
| 18 + 5\*Workday | 32659 | 35600 |
| 20 + 5\*Workday | 44113 | 43200 |

For energy costs, as shown in Fig. 8 (b-1) to (b-4), all kinds of energy costs nonlinearly increase with the increasing of temperature. For instance, compared with 14 + 5\*Workday, gas costs in January is increasing by approximately 22.6% for 16 + 5\*Workday. Compared with 18 + 5\*Workday and 20 + 5\*Workday, it will decrease by approximately 29.3% and 74.1% for 16 + 5\*Workday (Table 13), respectively.

For carbon emission, as illustrated in Fig. 8 (c-1) to (c-4), similar to energy costs, all kinds of carbon emissions will nonlinearly rise with increasing of temperature. Taking an example of carbon emission from gas Egas in January to illustrate, compared with 14 + 5\*Workday, Egas is increasing by approximately 22.5% for 16 + 5\*Workday. Compared with 18 + 5\*Workday and 20 + 5\*Workday, it will decrease by approximately 29.0% and 74.2% for 16 + 5\*Workday (Table 13), respectively.

Table 13: Comparison of gas costs and carbon emission in January among different set-points

|  |  |  |
| --- | --- | --- |
| Type | Gas costs in £  | Carbon emission in kg |
| 14 + 5\*Workday | 58700 | 3610 |
| 16 + 5\*Workday | 75800 | 4660 |
| 18 + 5\*Workday | 98000 | 6010 |
| 20 + 5\*Workday | 132000 | 8120 |

(a-1): (14 + 5\*Workday) oC @Energy

(a-2): (16 + 5\*Workday oC)@Energy

(a-3): (18 + 5\*Workday oC)@Energy

(a-4): (20 + 5\*Workday oC)@Energy

(b-1): (14 + 5\*Workday oC)@Costs

(b-2): (16 + 5\*Workday oC)@Costs

(b-3): (18 + 5\*Workday oC)@Costs

(b-4): (20 + 5\*Workday oC)@Costs

(c-1): (14 + 5\*Workday oC)@Emissions

(c-2): (16 + 5\*Workday oC)@Emissions

(c-3): (18 + 5\*Workday oC)@Emissions

(c-4): (20 + 5\*Workday oC)@Emissions

Fig. 8: Effect of indoor set-point temperature on energy (a) (Qheat, Qgasreal, Qhpelec, Qtankheat, Qhpeletank), costs (b) (Cgridhp, Cgas, Cgridtank) and carbon emissions (c) (Eelechp, Egas, Eelectank) for Building 1 under Mode 1.

* 1. **Effect of COP**

The COP of heat pump is another significant factor, which not only influences energy efficiency of BEN system but also affects the whole system energy costs and CO2 emissions, and it is beneficial to predict BEN system performance. The aforementioned boundary conditions are maintained excluding the COP of heat pump. Different COP levels, i.e., 2.6 (minimum design) and 3.9 (maximum design) have been simulated and compared with the benchmark case Mode 2 (real BEN system operation) with variable COP level for Building 1.

Figure 9 illustrates the influence of heat pump COP on energy (a), costs (b) and carbon emissions (c) for building 1 under Mode 2. Because the operating strategy Mode 2 for three different COP studied is the same, thus, the heating supplied by heat pump Qhpheat, actual gas usage Qgasreal, Mixergy tank heat Qtankheat are same. Meanwhile, the heating demand Qheat for three different COP studied is also the same due to the same building 1. According to Equs. (1) and (3), the electricity usage Qhpelec and Qhpeletotank are different. Taking an example of January to illustrate, for total energy demand, the electricity usage with variable COP Qhpelec is decreased by approximately 13.1% compared with COP 2.6. However, it will be increased by approximately 24.5% compared with COP 3.9 (Table 14). The above results could verify the variable COP of BEN system just lies within the design range of 2.6 to 3.9. Because the electricity usage supplying to heat pump should be a decreasing function of COP.

For energy costs, similar to energy demand, costs of actual gas usage Cgas in January for three different COP is same: 75839 £. However, costs of electricity usage Cgridhp and Cgridtank are different. Costs of the electricity usage with variable COP Cgridhp is decreased by approximately 14.4% compared with COP 2.6. It will be increased by approximately 23.7% compared with COP 3.9 (Table 14). In addition, the difference of Cgridtank is small, i.e., 12.28 £ (COP 2.6), 10.80 £ (variable) and 8.19 £ (COP 3.9) because of the cheap electricity price during midnight.

For carbon emissions, similar to energy costs, carbon emissions of actual gas usage Egas in January for three different COP is same: 4655 kg. However, carbon emissions of electricity usage Eelechp and Eelectank are different. Compared with COP 2.6, carbon emissions of the electricity usage with variable COP Eelechp is decreased by approximately 13.5%. It could be increased by approximately 24.3% compared with COP 3.9 (Table 14). Eelectank in January for variable COP is 390.9 kg, which is lower than COP 2.6 about 53.7 kg and higher than COP 3.9 around 94.5 kg.

Table 14: Comparison of electricity usage, costs and carbon emission in January among different COPs

|  |  |  |  |
| --- | --- | --- | --- |
| Type | Qhpelec in kWh  | Cgridhp in £ | Carbon emission for Eelechp in kg |
| Variable COP | 29000 | 24598 | 5674 |
| COP: 2.6 | 32800 | 28132 | 6442 |
| COP: 3.9 | 21900 | 18755 | 4295 |

(a-1) Variable COP: Monthly energy

(a-2) Variable COP: Monthly costs

(a-3) Variable COP: Monthly carbon emissions

(b-1) COP 2.6: Monthly energy

(b-2) COP 2.6: Monthly costs

(b-3) COP 2.6: Monthly carbon emissions

(c-1) COP 3.9: Monthly energy

(c-2) COP 3.9: Monthly costs

(c-3) COP 3.9: Monthly carbon emissions

Fig. 9: Effect of COP of heat pump on energy (Qheat, Qgasreal, Qhpelec, Qtankheat, Qhpeletank) (a), costs (Cgridhp, Cgas, Cgridtank) (b) and carbon emissions (Eelechp, Egas, Eelectank) (c) for Building 1 under Mode 2.

1. **Discussions and limitations**

According to the abovementioned results, because of water temperature within the pipeline connected with the borehole closer to surrounding air and ground temperature, cold water heat networks integrated in BEN system: next-generation energy networks could remarkably decrease heat losses via pipe heat transport. Currently, the supply/return temperature ultra-low-temperature district heating is approximately 40 oC/25 oC [21], therefore, BEN system can have a great perspective to expand the function of energy networks for low carbon infrastructure.

Output water temperature of borehole was set as a constant 14 oC on average in this study. Actually, it should be variable in the range of approximately 13 oC to 15 oC for London aquifer [2, 33-34].

Mode 3 is an optimal option from energy consumption, costs and carbon emission points of view, however, the investment cost and payback period should be considered. A full life cycle analysis will be conducted in the next-stage work.

The effect of humidity on building heat losses here was ignored, which results in that latent heat was not considered. Thermal losses of hot water from Mixergy thermal storage/heat pump to buildings through the envelope of component or pipework were neglected due to very close distance between them.

Other limits were mentioned in the section of Lists of assumptions.Those simplifications can facilitate data input and shrink computational time. Meanwhile, proposed integrated system model could fully embody real BEN operating principles and its set function.

1. **Conclusion and future work**

This article has numerically and experimentally studied performance of BEN system in LSBU, London based on internal factors for BEN and buildings. Several key results were drawn as follows: (1) Carbon emissions from building energy consumption mainly depend on operation mode and thermal storage capacity of BEN system, actual heat demand in buildings and carbon emission factor as a function of time; (2) Energy consumption and costs as well as its carbon emission will nonlinearly increase with the increasing of indoor set-point temperature; (3) With a favorable level of thermal comfort, in January (coldest month of the year), the heating consumption for operating BEN system will be decreased by 77.9%/72.9% compared with historic data of 2014/2015; (4) For BEN system, the usage, costs and carbon emissions of electricity is an decreasing function of COP; (5) Considering real BEN system and heat demand of two buildings at campus, system operation Mode 3 is an optimal mode compared with Modes 1 and 2.

In future, the study could be beneficial for next-generation energy networks design and optimization and provide the guidelines for similar BEN system. Future investigations, including an optimization of practical BEN, on-line monitoring and adjusting system parameters and set-point level, will be performed as task of the ongoing BEN project. In addition, the effects of external factors for BEN system, including weather conditions, carbon emission factors and electricity prices, on its performance will be investigated in our paper Part II.

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**Nomenclature**

*ACH* Air changes per hour

*ATES* Aquifer thermal energy storage

*BEIS* Department for Business, Energy and Industrial Strategy

*BEN* Balanced energy networks

*Cgas*  Actual gas costs

*Cheat*  Heating capacity

*Cgridhp*  Electricity costs for heat pump

*Cgridtank*  Electricity costs from heat pump for hot water tank

*Ct*  Total costs

*COP* Coefficient of performance for heat pump

*CWHN* Cold water heat networks

*DECC* Department of Energy & Climate Change

*DHN* District heating network

*DSR* Demand side response

*DNO* Diverse distribution network operator

*DUoS* Distribution use of system

*Eelechp*  Carbon emissions for grid supplying to heat pump

*Eelectank* Carbon emissions for Mixergy tank

*Egas*Carbon emissions for actual natural gas consumed

*Et*  Total carbon emissions

*ELT* Entering load temperature

*ESS* Energy system simulation

*EST* Entering source temperature

*GSHP* Ground source heat pump

*GSOMP*  Group search optimizer with multiple producers

*HVAC* Heating/cooling, ventilation and air-conditioning

*i*  time in hour

*j*  Building 1 (T-Block) and 2 (J-Block)

*LLT*  Leaving load temperature

*LPN* London power networks

*LSBU* London South Bank University

*MILP* Mixed integer linear programming

*MoGSO-ACL* Multi-objective group search optimizer with adaptive covariance and levy flights

*PD* Performance data

*Pheat*  Input work/power draw

*Qgas*  Gas usage for heating energy

*Qgasreal*  Actual gas usage for heating energy

*Qheat* Heat demand of building

*Qhpele* Electricity usage for heat pump

*Qhpeletotank* Electricity usage from heat pump for hot water tank

*Qhpheat* Heating energy supplied by heat pump

*Qta* Total annual energy consumption

*Qtankheat*  Heating energy supplied by tank storage

*Qtanke*  Electricity usage from heat pump for hot water tank

*TESS* Thermal energy system specialists

*TMY*  Typical meteorological year

*TRNSYS*  Transient system simulation program

*µ* Gas boiler efficiency and set as 0.9

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