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OPTIMAL OPERATION OF A MULTI-ENERGY SYSTEM: A CASE STUDY OF UNIVERSITY OF WARWICK'S ENERGY SYSTEM

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ABSTRACT

There has been growing concerns about climate change, and more environmentally friendly operation of energy systems is of high interest to energy systems owners. This study presents the optimal operation of the University of Warwick's energy system considering both energy and carbon emission costs. The system that currently consists of gas-fired CHP units, heat and electricity networks would be upgraded to a heat pump-based low-carbon energy system in 2050. A sensitivity analysis was conducted for both scenarios and provides insights into how sensitive the optimum solution is to different levels of demand, energy prices, and carbon price. The results show that a heat pump-based system is less sensitive to carbon emission price and has fewer carbon emissions than the existing CHP-based system.

Keywords: Decarbonisation, Integrated energy system

NOMENCLATURE

Abbreviations

AC	Absorption Chiller
CHP	Combined Heat and Power plant
COP	Coefficient Of Performance
EC	Electric Chiller
GB	Gas Boiler
HP	Heat Pump
TES	Thermal Energy Storage

Symbols and superscripts

g	Generation
d	Demand
η	Efficiency
pr	Price
t	Time step
E, H, C	Electricity, heating and cooling
ng	Natural gas
E/C	Electricity to cooling
G/H, G/E	Gas to heating, Gas to electricity
H/C	Heating to cooling
u	Binary decision variable for on/off
R	TES charge/discharge power limit

1. INTRODUCTION

In response to climate change, there have been substantial efforts in transforming current fossil fuel-based energy systems into sustainable and renewable-based energy systems. Existing operational practices need to be adapted to reduce not only operational costs but also environmental impacts. Optimal operations of sub-systems such as campus-scale energy systems could contribute to decarbonising the national system, and a coherent coordination among various energy infrastructures is critical. To this end, this paper examines optimal operations of the multi-energy system at University of Warwick's campus, which includes electricity, heating and gas as main energy carriers [1].

Energy hub [2] is one commonly used tool to deal with the operational optimisation in multi-energy systems mentioned above [3]. It models the units that are interfaced with multiple energy infrastructures with

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four main functionalities: input, conversion, storage and output [4]. In earlier study, optimal design and operation of a campus multi-energy system was reported in [5]. This paper provides a sensitivity analysis of optimal operation to various future scenarios, which has not been fully discussed in the existing literature.

This paper is organized as follows. Section 2 describes system configurations followed by energy hub modelling of each unit and a formulation of the overall operational optimisation. Section 3 presents the results in seven future scenarios. Finally, section 4 concludes this paper with remarks on future work.

2. METHOD

2.1 System description

The multi-energy system in University of Warwick's campus consists of CHP, GB, TES, EC and AC and the system configuration is illustrated in Fig 1(a). The system is connected with the external grid and could import electricity to satisfy electricity demand or satisfy cooling demand via EC. Note that current regulation does not allow the system to export electricity. The system also purchases gas to use in GB and CHP, which currently satisfy most of the electricity and heating demand. A water-based TES has been placed to provide operational flexibility to the system. The existing CHP has been scheduled to be replaced with multiple electric heat pumps in 2050 to decarbonise the system. The resultant system configuration is shown in Fig 1(b). In this study, it was assumed that several large-scale heat pumps with a COP of 4 would be installed around the campus with a total heat output capacity equal to the heat output capacity of the existing CHP.

Table 1 List of units in two system configurations

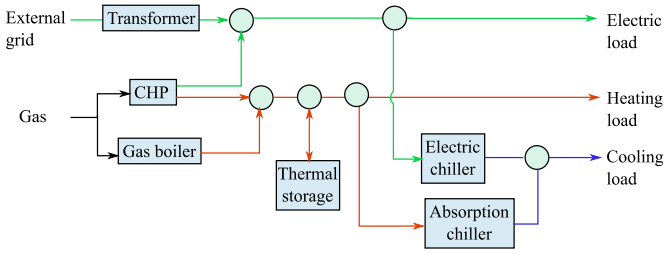
System configuration	Units
Scenario 1: CHP-based	CHP, GB, TES, EC, AC
Scenario 2: HP-based	HP, GB, TES, EC, AC

2.2 Models of energy conversion technologies

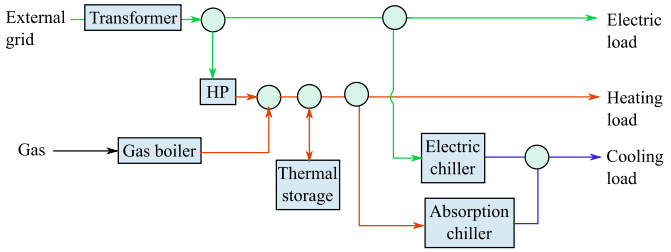
Each unit included in scenario 1 and scenario 2 was modelled using the energy hub approach and described as a simple relationship between input and output as follows.

$$g^{E}_{CHP,t} = m^{ng}_{CHP,t} \cdot \eta^{G/E}, \forall t \quad (1)$$

$$u_{CHP,t} \cdot \underline{g}^{E}_{CHP,t} \le g^{E}_{CHP,t} \le u_{CHP,t} \cdot \bar{g}^{E}_{CHP,t}, \forall t \quad (2)$$



(a) Scenario 1: present



(b) Scenario 2: year 2050

Fig 1 System configurations

$$g^{H}_{CHP,t} = m^{ng}_{CHP,t} \cdot \eta^{G/H}, \forall t \quad (3)$$

$$u_{CHP,t} \cdot \underline{g}^{H}_{CHP,t} \le g^{H}_{CHP,t} \le u_{CHP,t} \cdot \bar{g}^{H}_{CHP,t}, \forall t \quad (4)$$

$$g^{H}_{HP,t} = \mathrm{COP} \cdot d^{E}_{HP,t} \ \forall t \quad (5)$$

$$u_{HP,t} \cdot \underline{g}^{H}_{HP,t} \le g^{H}_{HP,t} \le u_{HP,t} \cdot \bar{g}^{H}_{HP,t}, \forall t \quad (6)$$

$$g^{C}_{EC,t} = d^{E}_{EC,t} \cdot \eta^{E/C}, \forall t \quad (7)$$

$$\underline{g}^{C}_{EC,t} \le g^{C}_{EC,t} \le \bar{g}^{C}_{EC,t}, \forall t \quad (8)$$

$$g^{C}_{AC,t} = d^{H}_{AC,t} \cdot \eta^{H/C}, \forall t \quad (9)$$

$$\underline{g}^{C}_{AC,t} \le g^{C}_{AC,t} \le \bar{g}^{C}_{AC,t}, \forall t \quad (10)$$

$$g^{H}_{GB,t} = m^{ng}_{GB,t} \cdot \eta^{G/H}, \forall t \quad (11)$$

$$\underline{g}^{H}_{GB,t} \le g^{H}_{GB,t} \le \bar{g}^{H}_{GB,t}, \forall t \quad (12)$$

$$\underline{E}^{H}_{TES,t} \le E^{H}_{TES,t} \le \bar{E}^{H}_{TES,t}, \forall t \quad (13)$$

$$-R_{\mathrm{discharge}} \le E^{H}_{TES,t+1} - E^{H}_{TES,t} \le R_{\mathrm{charge}}, \forall t \quad (14)$$

where Eqs. (1) - (12) model electricity, heating and cooling output from CHP, GB, HP, AC and EC with their corresponding capacity limits. Eq. (13) formulates TES's heat storage level. TES's charge and discharge rates are constrained as in Eq. (14). Binary variables $u_{CHP,t} \in \{0,1\}$ and $u_{HP,t} \in \{0,1\}$ in Eqs. (2), (4) and (6) model the minimum output of CHP and HP.

2.3 Energy balance constraints

The energy in each type of carrier needs to be balanced, and end-user demands should be strictly respected. These are formulated as in Eqs. (15) - (17).

$$g^{E}_{CHP,t} + g^{E,\mathrm{import}}_{t} - d^{E}_{EC,t} = d^{E}_{L,t} \quad (15)$$

$$\sum_{i\in \mathrm{CHP,GB,HP}} g_{i,t}^{H} - \sum_{i\in \mathrm{AC}} d_{i,t}^{H} - d_{t}^{H,\mathrm{dump}} + E_{TES,t} - E_{TES,t+1} = d_{L,t}^{H} \quad (16)$$

$$\sum_{i\in \mathrm{AC,EC}} g_{i,t}^{C} = d_{L,t}^{C} \quad (17)$$

where $g_{i,t}^{E}$ and $g_{i,t}^{H}$ denote the electricity and the heat output, $d_{L,t}^{E}$, $d_{L,t}^{H}$ and $d_{L,t}^{C}$ are respectively the end-user demands for electricity, heating and cooling, $g_{t}^{E,\mathrm{import}}$ is the amount of imported electricity. Note that either CHP or HP appears in Eq. (16). Throughout the paper, both generation g and demand d are non-negative

2.4 Optimisation formulation

The operational costs consist of three parts: the cost of imported electricity; the cost of purchased natural gas; and the penalty for carbon emission. Hence, the overall operational optimisation problem could be formulated as follows.

$$\text{Minimize} \quad pr_{\mathrm{el}} \cdot \sum_{t} P_{t}^{E,\mathrm{import}} + pr_{\mathrm{gas}} \cdot \sum_{t} m_{t}^{\mathrm{ng}} + pr_{\mathrm{carbon}} \cdot \sum_{t} m_{t}^{\mathrm{carbon}}$$

Subject to Eqs. (1) - (17)

The impacts of carbon emissions on optimal system operations were evaluated over a range of carbon emission price pr_{carbon} in the next section.

3. RESULTS

The parameters of each unit and economic metrics of each scenario summarised in Table 2 and Table 3 are based on [6] and [7], which provide projections for UK in 2035. To study the optimal operation in 2050, we have created multiple scenarios to reflect further projections in 2050. Scenario 1 (Sce 1) was used as a benchmark to illustrate the operational practices of existing CHP-based system. Sce 2a was used as a reference scenario for HP-based system in 2050. It took the projections for 2035 as main inputs and used the load profiles from the current system to obtain optimal operation throughout the year. Sce 2b to Sce 2g share a same system configuration with variations in the energy prices, the electricity carbon intensity and end-user demand levels. The differences are summarised in Table 3. Note that, load patterns were assumed to be the same as those in the current system and scaling factors were used to indicate the changes in demand levels. We neglected the impacts of emerging electric loads such as electric vehicles, which could change the electrical load patterns dramatically.

Table 2 Characteristics of components

Unit	Electricity capacity	Thermal/Cooling capacity	Minimum load
CHP	8.6 MW_e	8.8 MW_{th}	66%
HP	220 kW_e	880 kW_{th}	80%
GB	N/A	14.98 MW_{th}	N/A
EC	0.66 MW_{co}	2 MW_{co}	N/A
AC	1.7 MW_{co}	1.2 MW_{co}	N/A
TES	N/A	8.71 MWh_{th}	N/A

Table 3 Scenarios for sensitivity analysis

Sce 1 - CHP-based		
Energy carrier	Price	Emission intensity
Electricity	0.118 £/kWh_e	144 $gCO2/kWh_e$
Gas	0.026 £/kWh_{gas}	210 $gCO2/kWh_{gas}$
Sce 2a - HP-based: reference		
Energy carrier	Price	Emission intensity
Electricity	0.127 £/kWh_e	44 $gCO2/kWh_e$
Gas	0.032 £/kWh_{gas}	210 $gCO2/kWh_{gas}$
Sce 2b - HP-based: high electricity and low gas price		
Energy carrier	Price	Emission intensity
Electricity	0.136 £/kWh_e	44 $gCO2/kWh_e$
Gas	0.0267 £/kWh_{gas}	210 $gCO2/kWh_{gas}$
Sce 2c - HP-based: low electricity and high gas price		
Energy carrier	Price	Emission intensity
Electricity	0.118 £/kWh_e	44 $gCO2/kWh_e$
Gas	0.0384 £/kWh_{gas}	210 $gCO2/kWh_{gas}$
Sce 2d - HP-based: low el carbon intensity		
Energy carrier	Price	Emission intensity
Electricity	0.127 £/kWh_e	14.7 $gCO2/kWh_e$
Gas	0.032 £/kWh_{gas}	210 $gCO2/kWh_{gas}$
Sce 2e - HP-based: medium el carbon intensity		
Energy carrier	Price	Emission intensity
Electricity	0.127 £/kWh_e	22 $gCO2/kWh_e$
Gas	0.032 £/kWh_{gas}	210 $gCO2/kWh_{gas}$
Sce 2f - HP-based: high electricity and thermal load		
Energy carrier		Load scaling factor
Electricity, heating and cooling		1.2
Sce 2g - HP-based: low electricity and thermal load		
Energy carrier		Load scaling factor
Electricity, heating and cooling		0.8

The optimisation problem presented in the previous section was formulated using YALMIP [8] to solve in MATLAB. The operations were optimised based on the historical hourly energy demand measurements of an entire year. The total costs for imported electricity and

natural gas and carbon emissions in all scenarios are presented in Fig 2 with respect to a range of carbon emission prices.

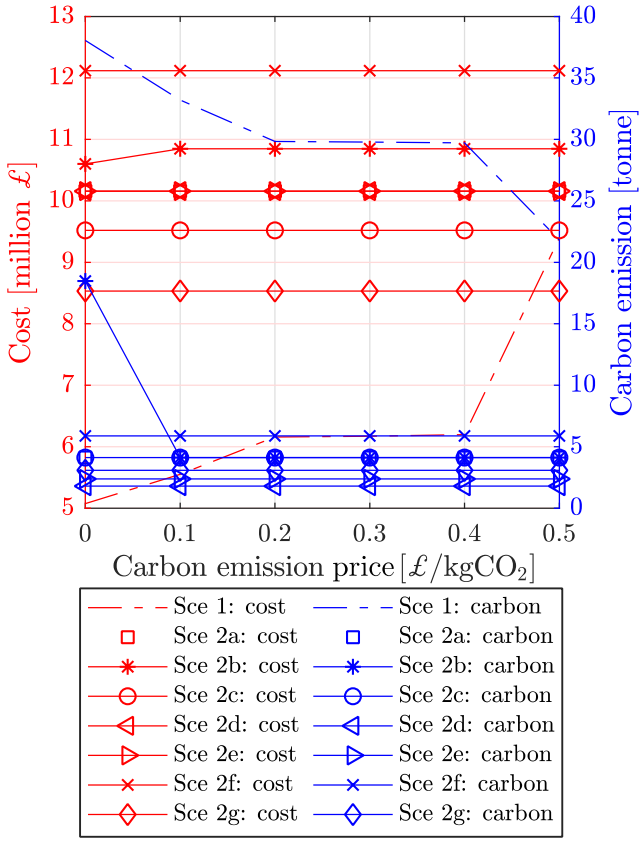


Fig 2 Comparison of results in all scenarios.

From Fig 2, it could be observed that in all scenarios the carbon emissions decrease as the carbon emission price increases at the expense of increased operational costs. Of all the scenarios, carbon emission penalties affect the CHP-based system (Sce 1) most significantly. The gas consumption was penalized while the electricity usage was promoted. The same trend could also be observed in Sce 2b. In contrast, changes in carbon emission price do not have visible impacts on operational costs and carbon emissions in Sce 2a and Sce 2c - Sce 2g. We could also observed that the operational costs in HP-based system were lower than Sce 1 only when the end-user demand could be reduced by 20% (Sec 2g). Moreover, in all HP-based systems, the carbon emissions are lower than the CHP-based system, thanks to HP's high energy efficiency.

4. CONCLUSION

This study investigates the optimal operation of the energy system at the University of Warwick. The operation of both the existing CHP-based system and the planned heat pump-based system were optimized considering energy costs and carbon emission penalties. Seven future scenarios were created to reflect the potential energy prices, carbon emission prices and energy demand levels in 2050. A sensitivity analysis shows that the heat pump-based system is less sensitive to carbon emission costs and has less carbon emissions than the existing CHP-based system.

The study neglected the hydraulic and thermal constraints in the district heating network. Future work will validate the calculated optimal operation in detailed district heating simulation.

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