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INVESTMENT ANALYSIS AND SIZING OF A HEAT PUMP IN A MULTI-VECTOR ENERGY SYSTEM: A CASE STUDY AT UNIVERSITY OF WARWICK

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ABSTRACT

This paper presents a methodology to evaluate the whole system energy-economic-environmental performance and the economic viability of integrating new technology options such as heat pumps, energy storage units to an existing multi-vector energy system. The transition to a low carbon energy system would require that decisions to invest in new low carbon technology in local energy supply systems carefully consider the choice of technology as there are a plethora of technology options available with varying degrees of uncertainty to reach the same destination. The methodology is applied on a real campus multi-vector energy system to evaluate the whole system performance and economic viability of integrating heat pumps to its existing energy system that depends on gas fired CHP and gas boilers for its heat supply.

Keywords: heat pump, investment analysis, whole system analysis, campus multi-vector energy systems

1. INTRODUCTION

Climate change concerns necessitate the adoption of low carbon technology options such as solar PV, on-site wind turbines, heat pumps and electricity storage for local energy supply. Multitudes of such technology are promoted as options to reduce carbon emissions and enable local energy system improvements for organisations where the cost of energy and its environmental footprint is a significant concern.

However, in numerous examples, ad-hoc investments in new energy technologies have led to operational issues in existing systems and instances where the capital costs were not recovered as expected. The reasons were identified as the inappropriate choice of technology for a particular system configuration, technology sizing and challenges to upgrade local energy management systems.

There is a need for a methodology/modelling tool to evaluate investment options and to design the size of a new technology considering the system's multi-energy load profile (electricity, heat, gas, cooling) system configuration technology costs (capital, O&M) and technology characteristics (efficiency, lifetime) weather conditions at the location (solar irradiation, wind speed) economic parameters - energy import, and export tariffs, discount rates, project lifetime.

A review of methods and performance criteria used to assess the energy and environmental performance and design of integrated energy systems was carried out in [1]. Traditionally, the discounted cash flow method using NPV (net present value), IRR (internal rate of return) and payback time indicators are used to assess the profitability of a new technology investment. However, there are no widely accepted tools available to evaluate the potential energy-economic and environmental benefit of new technology investments on an integrated multi vector energy system that capture whole system benefits.

This paper presents a method for estimating the economic viability and energy-economic-environmental performance of new technology in an integrated multi-vector energy system. A case study demonstrates the method applied to study the integration of a heat pump in a multi-vector energy system to achieve particular carbon target.

2. *PROBLEM DESCRIPTION*

2.1 *System Configuration*

Fig 1 shows a schematic diagram of this system. It consists of an onsite electricity distribution network and a district heating network across the campus. Different energy supply networks are interconnected via combined heat and power units, gas boilers, electric chillers and absorption chillers. Thermal storage units are used to support the operation of the district heating system, which can also support the electricity network indirectly.

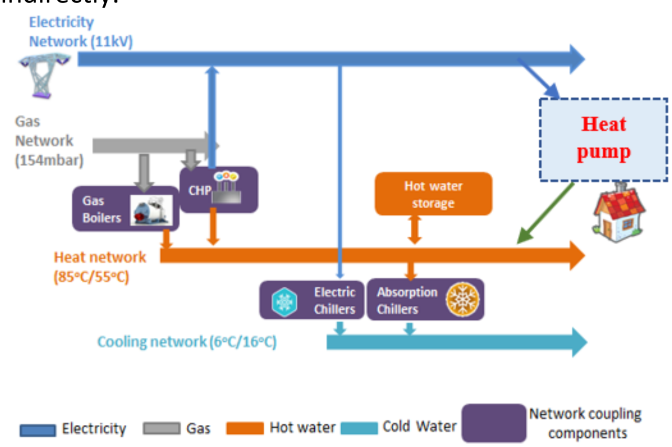

Fig 1 Schematic of the energy supply system at University of Warwick with new technology installations

2.2 *Investment options assessment*

The facility manager intends to invest in heat pumps or other options to improve the performance the energy system. To support the decision-making process, it is required to quantify the potential benefit of such an investment and to size these units from a whole system point of view.

3. *METHODOLOGY*

In this paper, a systematic method is proposed for investment option assessment as shown in Fig 2.

3.1 *Problem formulation for operational optimisation*

The objective is to minimize the operating cost of the system including electricity, gas and carbon emission.

$$Min \sum_{t=1}^{n_T} \frac{c_{buy,e}(t) + c_{sell,e}(t)}{2} P_{ex}^{e}(t) + \frac{c_{buy,e}(t) - c_{sell,e}(t)}{2} |P_{ex}^{e}(t)| + (c_g + c_c) P_{ex}^{g}(t) \quad (1)$$

where $c_{buy,e}(t)$ and $c_{sell,e}(t)$ are import and export prices of electricity. $c_g(t)$ is the natural gas price. c_c is the carbon price. $P_{ex}^{e}(t)$ is the electricity import from the power grid (positive) and export to the power grid (negative). $P_{ex}^{g}(t)$ is the import gas from the gas grid.

The power and heat generators are constrained by

$$\underline{P}_{chp,j}^{e} \le P_{chp,j}^{e}(t) \le \overline{P}_{chp,j}^{e} \quad (2)$$

$$\overline{P}_{boiler,k} \le P_{boiler,k}(t) \le \overline{P}_{boiler,k} \quad (3)$$

$$\overline{P}_{hp,h} \le P_{hp,h}(t) \le \overline{P}_{hp,h} \quad (4)$$

where $P_{chp,j}^{e}(t)$ is the power output of the j^{th} CHP at time t, $P_{chp,j}^{e}(t) = P_{chp,j}^{g}(t)\eta_{chp,j}^{e}.\eta_{chp,j}^{e}$ is the power output efficiency of the j^{th} CHP. $\underline{P}_{chp,j}^{e}$. $P_{boiler,k}^{e}(t)$ is the heat output of the k^{th} boiler at time t. $P_{hp,h}(t)$ is the heat output of the h^{th} heat pump at time t.

The balance of electricity is expressed as

$$\sum_{j=1}^{n_{chp}} P_{chp,j}^{e}(t) + \sum_{i=1}^{n_{ec}} P_{se,i}(t) + \sum_{i=1}^{n_{ec}} P_{ex}^{e}(t) = \sum_{h=1}^{n_{hp}} P_{hp,h}(t)/\eta_{hp} + \sum_{l=1}^{n_{lc}} P_{c}^{l}(t) \quad (5)$$

where $P_{st,i}(t)$ is the imported electricity of the i^{th} energy centre. n_{ec} is the number of energy centres. $P_{c}^{l}(t)$ is the l^{th} electricity demand. n_{lc} is the number of demands. n_{chp} and n_{hp} are the number of CHP and heat pumps. $\eta_{hp,h}$ is the efficiency of the h^{th} heat pump.

The balance of heat is constrained by

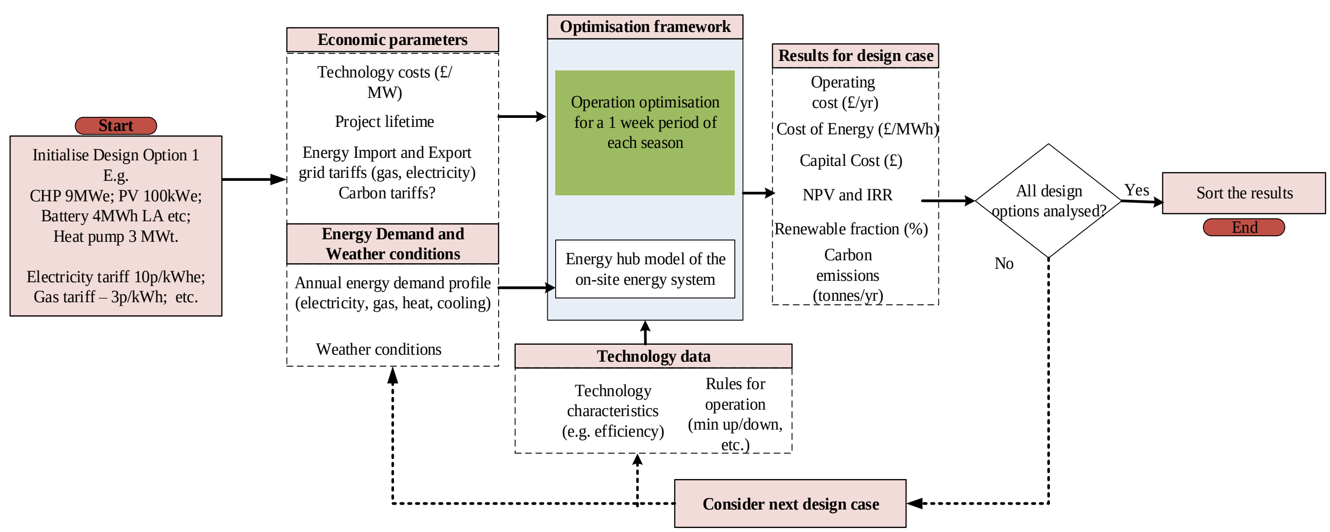

Fig 2 Proposed investment assessment methodology

$$0 \le \sum_{j=1}^{n_{chp}} P_{chp,j}^{g}(t)\eta_{chp,j}^{h} + \sum_{k=1}^{n_{boiler}} P_{boiler,k}^{g}(t) * \eta_{boiler,k}^{h} - \sum_{i=1}^{n_{ec}} P_{st,i}(t) - \sum_{l=1}^{n_c} P_c^l(t) \le \overline{P}_{dump} \quad (6)$$

where η_{chp}^{h} is the heat output efficiency of the CHP. $P_{chp,j}^{h}(t)$ is the heat output of the j^{th} CHP at time t. $\eta_{boiler,k}^{h}$ is the efficiency of k^{th} boiler.

The operation of thermal storage is constrained by

$$E_{sh,i}(t+\Delta t) = E_{sh,i}(t) - P_{sh,i}(t)\Delta t \quad (7)$$

$$\underline{E}_{sh,i} \le E_{sh,i}(t) \le \overline{E}_{sh,i} \quad (8)$$

$$\underline{P}_{sh,i} \le P_{sh,i}(t) \le \overline{P}_{sh,i} \quad (9)$$

$$E_{sh,i}(nT_{day}) - E_{sh,i}(0) = 0 \quad (10)$$

where $E_{sh}(t)$ is the amount of heat in the water tank. $P_{sh}(t)$ is the heat output of the water tank. $\underline{E}_{sh,i}$ and $\overline{E}_{sh,i}$ are the minimum and maximum amount of energy in the i^{th} water tank. $\underline{P}_{se,i}$ and $\overline{P}_{se,i}$ are the maximum discharging and charging heat of the i^{th} water tank. $E_{se,i}(nT_{day})$ and $E_{se,i}(0)$ are the heat in the storage at the start time of each day.

3.2 Scheme of investment options assessment

The proposed methodology is described below.

Step 1: A range of capacities are pre-selected for generating design options of heat pumps. The benefits of design options are evaluated iteratively.

Step 2: In each iteration, a technology configuration is generated by incorporating economic parameters, energy demand weather profiles, and technology data.

Step 3: An optimisation of the operation is carried out for a representative one-week period of each season (winter, summer etc.) for the given system configuration.

Step 4: The results of this optimization (e.g. operating cost and carbon emissions for one-week in each season) are used to assess the operation results for one year. The annual operation results and the technology cost data are used to carry out the investment analysis.

Step 5: The next design option is considered for the next iteration.

Step 6: The best option is acquired by ranking the results for all design options.

4. CASE STUDY

4.1 System description

The proposed method is applied to the campus multi-vector energy system as shown in Fig 1. Details of the energy centres are depicted in Table 1. The total capacity of the water tanks is 8.511 MWh. The heat and electricity demand of one year (2016) is shown in Fig 3.

Table 1 Parameter of the two energy centres.

	Equipment	Capacity	Minimum output
Energy centre I	CHP	3 x 1.4 MWe	66.66%
	Gas boiler	2 x 4.87 MWt	
	Water tank	100 m3	
Energy centre II	CHP	2 x 2 MWe	50 %
	Gas boiler	5.24 MWh	
	Water tank	100 x 2 m^3	

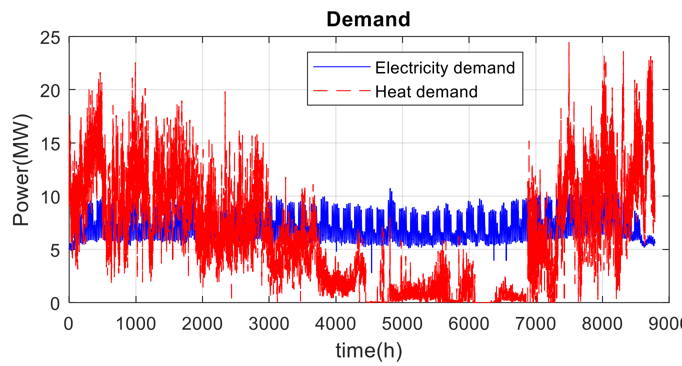

Fig 3 Heat and electricity demands

4.2 Economic parameters

The import gas price is 0.02214 £/kWh. The imported electricity price with off-peak and peak values are 0.05217 £/kWh (0:00-8:00) and 0.07713 £/kWh (9:00-24:00). Feed-in tariff is not considered.

Carbon emission of natural gas is 0.185 kg/kWh. Three levels of carbon prices, namely 0 £/t, 30 £/t, and 70 £/t are considered for assessing the investment on heat pumps.

The IRR and the NPV are studied in the investment analysis.

$$NPV = \sum_{t=0}^{n} \frac{C_t}{(1+r)^t} - C_0 \quad (11)$$

where r is the discount rate (7.2% is used in this paper). t is the number of time periods. C_t is the net cash flow during a single period t. C_0 is the total initial investment costs. The IRR is a r that makes the NPV of all cash flows from a particular project equal to zero.

The lifespan of the heat pump is 25 years. The price of the heat pump is 400000 £/MW with the operating cost 1793 £/MW [2].

5. RESULTS AND DISCUSSION

In this section, the optimal operation result of the current system is studied as a reference case. Then the assessment for heat pump are carried out separately.

5.1 Impact of heat pump price

In this case, it is assumed that the carbon tax is 70 £/t and there is no PV panes installed on-site. For the instalment of heat pumps, the IRR, the NPV, and the carbon emission of the investment are shown in Fig 4.

The results show the investment has the maximum NPV when the capacity of the heat pump is 5 MW. However, to reduce 80% of carbon emission which is the target of UK government, the capacity of heat pump needs to reach 7 MW.

When the price of the heat pump is above 48 £/kW, the NPV of the investment becomes negative, which indicate using heat pumps to achieve the decarbonisation target is not economic viable.

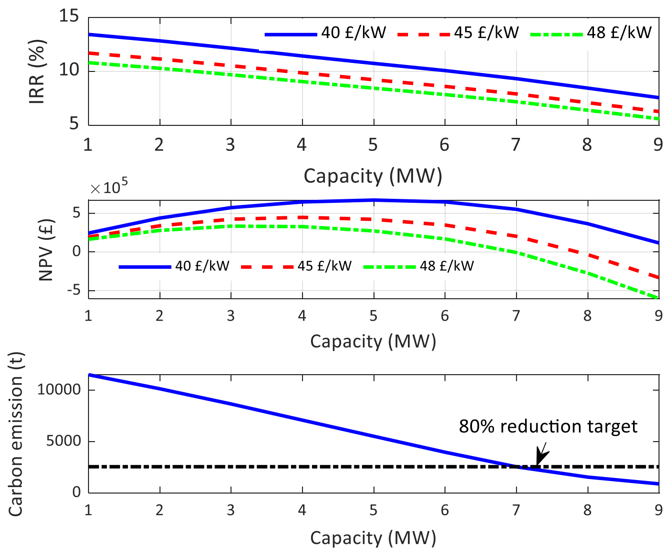

Fig 4 The IRR and the NPV in reference to the capacity of heat pumps

5.2 Impact of carbon price

Assume that the price of the heat pump is 40 £/kW, the carbon emission of the campus energy system is shown in Fig 5. It can be seen that under the current pricing condition of electricity, gas, and heat pumps, CHP and boiler will be chosen to supply heat when the carbon tax is at a low level. Therefore, a high carbon tax (70 £/t) is required in order to promote the application of heat pumps and reduce the carbon emission of the campus energy system.

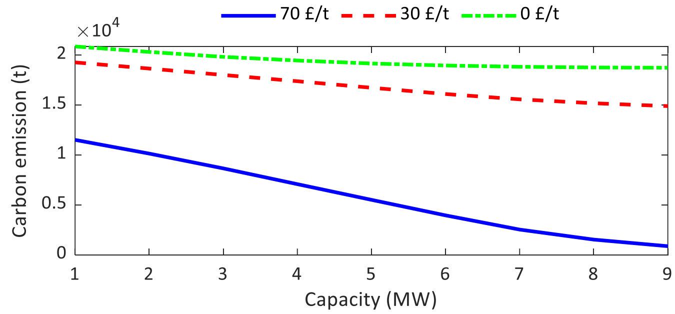

Fig 5 Carbon emission reduced by using heat pumps under different carbon tax.

6. CONCLUSIONS

This paper investigates the instalment of heat pump for reducing the carbon emission of the campus energy system at a university campus in the UK. The maximum acceptable price of installing heat pump is obtained based the current price of electricity, gas and carbon tax. The results also show that a high carbon tax rate is required in order to support the instalment of heat pumps.

Note that the discount rate refers to the low risk scenario in this case, a higher discount rate will reduce the feasibility of investment regarding the NPV. Also, the efficiency and price of the heat pump may be variable at different capacities. More work is required for assessing the investment options.

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