A decision support tool for improving energy and environmental performance of public sector multi-energy systems

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Abstract
The public sector is estimated to consume 6% of the UK's energy, spends around £3.4 billion per annum on its energy bill and is expected by the UK Government to lead the de-carbonisation agenda. Many of the larger public sector establishments such as hospitals and universities own and operate their own multi-energy supply systems and there is a clear need to reduce their energy use, carbon footprint and manage their costs of operation.

Many public sector campus energy systems use combined heat and power generators (CHP) and increasingly include a range of on-site renewable energy technologies (e.g. wind turbines and solar panels) and energy conversion technologies such as gas boilers, electrical and absorption chillers, and heat and electricity storage. They typically have long-term commercial agreements for buying electricity and gas, and if excess electricity available for selling power back to the network.

This paper presents an overview of the challenges facing the public sector in the energy transition and the design methodology of a decision support tool for assessing operation improvement opportunities. A case study of a hospital site where the decision support tool was implemented is presented. The tool captures different objectives of an energy manager in the public sector estate (e.g. cost minimisation, carbon emission reduction) and generates key performance indicators (KPIs) that enable useful comparisons. The energy system behaviour of the site is characterised in detail. The study demonstrated an annual energy cost saving potential of 12% was available from optimising the CHP generator operation at the hospital site. The study also illustrates the dichotomy between the two competing objectives, cost optimisation and carbon savings from the utilisation of CHP units due to low natural gas prices and the resulting challenge for decision making for the estate energy managers.

1 Introduction

Local energy systems are a growing feature of energy supply systems across the world [1]. In the UK, active participation of local communities and organisations to decarbonisation goals has been further reinforced by the government's commitment to NetZero emissions by 2050 [2,3]. At the same time, national electricity grid operators are facing a growing challenge to operate the power grid with an increasing share of intermittent renewable power generation, increased electrical loads such as Electric vehicles and heat pumps being connected at the distribution level and reduced system inertia requiring additional flexible resources to maintain system reliability [4].

The UK governments' NetZero ambition and the wider power system challenges are driving campus energy systems particularly in public sector to reduce individual carbon footprint by investing on renewable generation, low carbon heating and energy storage technologies. There is a significant opportunity for these sites to be active participants of the power system by providing power grid services to support efficient management of the grid operation [6].

The public sector consumes 6% of the UK's energy, spends around £3.4 billion per annum on its energy bill and is expected by the UK Government to lead the de-carbonisation agenda [5]. The higher education sector has a voluntary target of a 30% reduction in greenhouse gas emissions by 2020/21 across its estate with a view to increase this to 50% by 2030 compared to 1990 levels. As the largest public sector emitter of carbon emissions, the health system is expected to meet the UK's de-carbonisation targets by contributing 80% reduction in carbon emissions by 2028-2032 and net-zero on direct emissions by 2040 [6].

Many of the larger public sector establishments such as hospitals and universities own and operate their own multi-energy supply systems and there is a clear need to reduce their energy use, carbon footprint and at least control their costs of operation.

Currently, there are no tools available to quantify the potential gains of optimising the operation of these energy supply. The operation and control strategies of the on-site energy management systems are presently rather simple. They are typically based on a set of pre-specified rules designed to guarantee that local energy demands (mainly heat) are served. While academic research investigates new and sophisticated control strategies [7-8] the gap between academic research and the simple approaches required by site energy mangers hinders the potential benefits of local multi energy systems from being realised.

This paper presents an overview of the challenges facing the public sector in the energy transition and a methodology for developing a decision support tool to evaluate operation improvement opportunities at a campus site. A case study demonstrating the decision support tool applied at a hospital site is presented in detail.

The project was undertaken by researchers at Cardiff University in partnership with the UK Cabinet Office and the estate office energy managers at Queen Elizabeth Hospital (QEH), Kings Lynn and University of Warwick (UoW) and was funded by the National Centre for Energy Systems Integration.

2 Campus energy systems, challenges, and decision support tools

Campus energy systems are site based local energy systems and large users of electricity and heat (hospitals, business parks, universities etc.). Their on-site energy systems are complex and typically contain multiple energy assets such as renewable power generation (solar PV or wind turbines), combined heat and power (CHP) generation units, gas boilers and energy storage. Campus energy systems are controlled 'behind the meter', typically to reduce site energy costs. Collectively many such campus systems across a region may aggregate to a significant scale which depending on the way they are operated can either assist or aggravate power flows on the local electricity distribution and transmission networks. Campus energy systems are well placed to be smart, active participants of the wider power system and support efficient management of the grid operation.

A typical campus energy system structure is shown in the figure below:

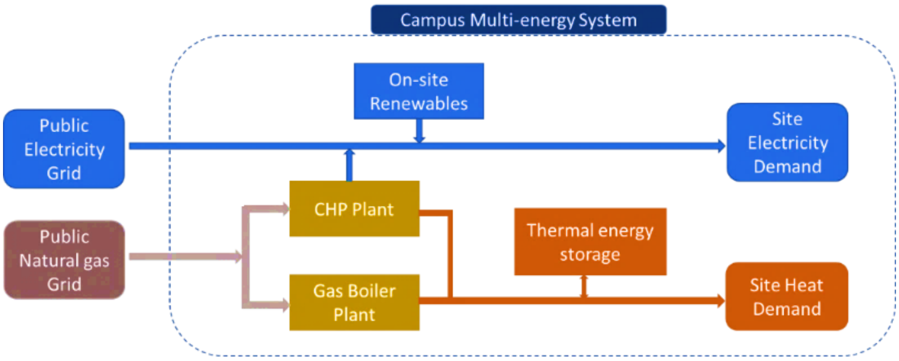


Figure 1: General arrangement of a campus multi-energy system

The operation and control strategies of the on-site energy management systems are presently rather simple. They are typically based on a set of pre-specified (static) dispatch rules designed to guarantee that local energy demands (mainly heat) are served. Commercial agreements are in place for buying electricity and gas, and for selling electricity back to the network (if electricity exports are permitted).

To optimise energy costs and carbon emissions, the operation strategy of the on-site energy system should consider:

- Half hourly electricity price fluctuations (selling price, buying and distribution charges)
- Weather conditions
- On-site renewable energy generation
- Estimates of carbon dioxide emissions
- Opportunities for energy conversion on-site and
- Optimal management of energy storage systems considering the synergies between different energy systems

2.1 Challenges faced by public sector energy managers

The public sector faces significant challenges to address the energy system improvement ambitions. Some of the key challenges concluded in a workshop organized for this research project were:

Common challenges

- Energy system is one of many priorities
- System resilience more important than efficiency
- Aged infrastructure and obsolete equipment
- Financial constraints and lack of engagement with the energy system → Lack of investment
- Lack of an energy strategy

Other more technical challenges

- Carbon savings not anymore aligned with using gas fired CHP generators
- Reluctance of designers and contractors to deviate from traditional technologies

- Conflicting systems as new infrastructure added on to site
- Local electricity network constraints
- Complexities and uncertainties in the energy sector delay decisions

2.2 Requirement of decision support tools

It was found there is a lack of accessible, user friendly decision support tools that would inform and guide estate managers to make informed decisions to improving on-site energy systems. The following features were identified as important for a decision support tool aiming to support public sector energy managers:

- Capture multiple site objectives (resilience, cost, emissions) and provide evidence on key performance indicators
- Capture internal and external factors that influence decisions
  For example, an investment in battery storage should consider how it fits with other on-site assets and the potential for conflicts and how it might make additional revenue by providing grid services to the local DNP
- Does not have onerous Initial data requirements as this would add to the workload of already fully stretched energy officers in these organisations.

3 Methodology

This study focuses on the design and implementation of a campus energy performance improvement opportunity assessment tool for public estate energy managers. It is applicable for any site with on-site energy generation, conversion, and storage opportunities.

3.1 Decision support tool development process

The steps of the decision support tool development methodology are shown in Figure 2.

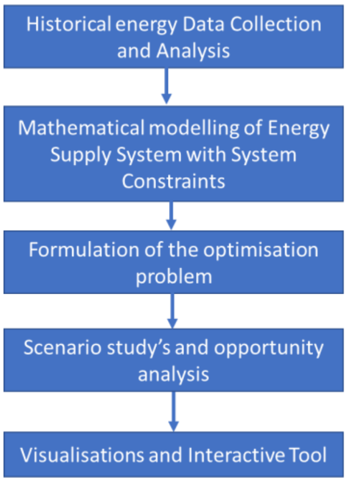


Figure 2: Process of the decision support tool development process

The process of developing a decision support tool includes collection of historical energy data and analysis to identify behavioural patterns, developing a simplified mathematical model of the on-site energy system, formulation of the optimisation problem based on the requirements of the site and then running different scenarios to identifying performance improvement opportunities. Final step of this process was to develop an interactive decision support tool with engaging visualisations that could communicate information clearly to a non-technical individual.

3.2 Structure of the decision support tool

The mathematical modelling is an important part of the decision tool as it allows to run optimisation routines for site operation and compare with historical performance.

The campus multi-energy system was modelled using the concept of energy hubs [10-12]. An energy hub model describes the steady-state power flows within a multi-energy system based on the balance of the supply and demand of each energy vector (e.g., electricity, heat) for each period. The model represents energy conversion, energy import and exports, and energy storage. The energy networks are not considered. It uses static inputs characterising the technical and commercial arrangements of the on-site energy system and an operational constraint and the operation objective such as cost minimisation or carbon or a weighted objective. The model then simulates the optimal operation for a given electricity and heat demand and energy prices and generates an output of the operational and dispatch characteristics of the on-site assets.

Figure 3 shows the inputs and outputs of the mathematical model for the campus energy system developed based on Energy flows.

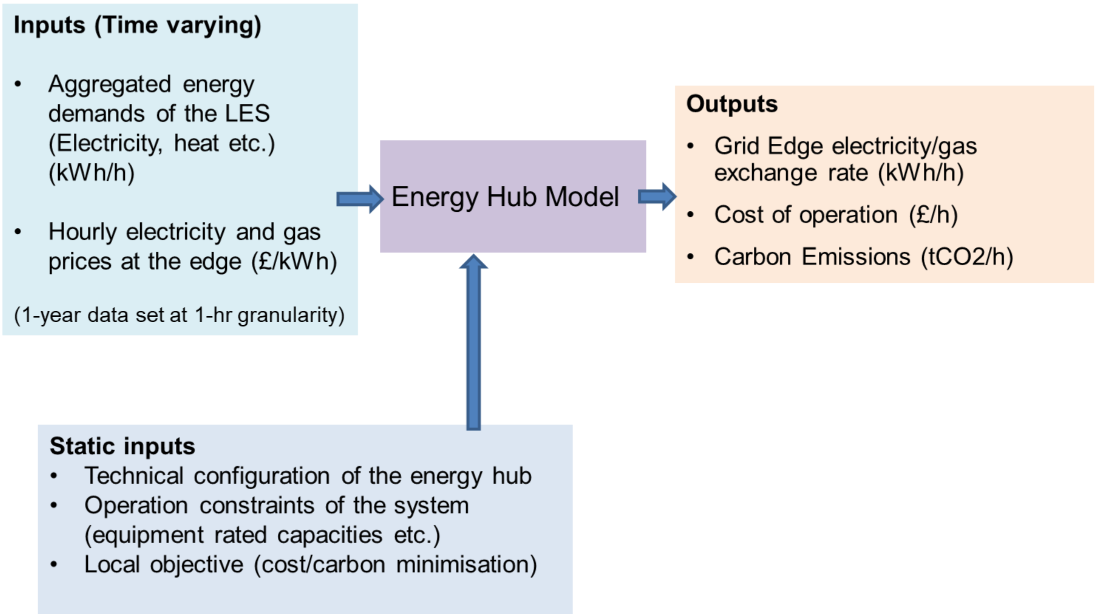


Figure 3: Inputs and Outputs of the Campus Energy Systems model

The time resolution of the simulations is based on the granularity of the available time varying input data. In this paper an hourly time granularity is used for the case study presented in the following section.

4 Case study and demonstration of the decision support tool

4.1 Case study

Queen Elizabeth Hospital (QEH) is a regional hospital in Kings Lynn, Norfolk, UK. The QEH NHS Trust owns and operates a multi-vector energy system on-site which includes 2 combined heat and power units and a wind turbine (owned by a third party). Unique for a hospital site, QEH often produces excess electricity than the site demand due to the output from the wind turbine and the output from CHP units exceeding site electricity demand. QEH has agreed a 200kW electricity export connection with the local electricity network operation. A commercial arrangement for the sale of excess electricity exports has been agreed with an energy supplier. A simplified illustration of the technical arrangement of the on-site multi-energy system and the commercial arrangements for electricity imports and exports at QEH are shown in Figure 4.

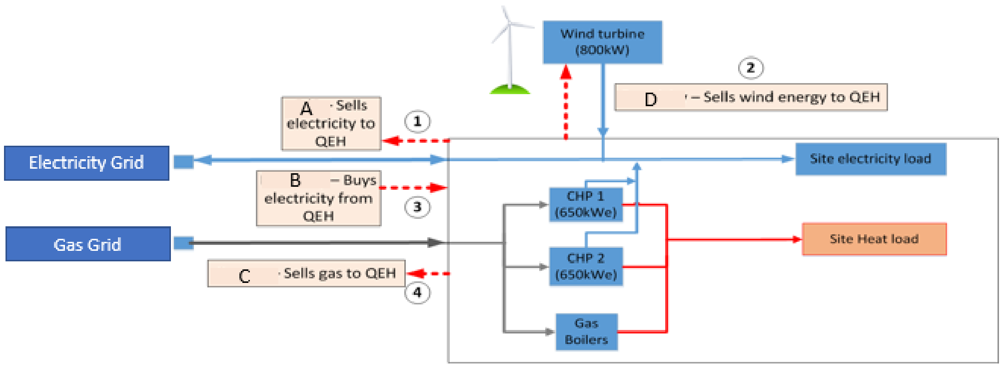


Figure 4: Schematic of the energy supply system and the commercial arrangements for energy purchase and sale at QEH

A summary of the technical characteristics of the on-site energy infrastructure is provided in table 1.

Table 1: Technical data for QEH energy assets

System		Capacity	Notes
Electricity	Gas fired CHP units	2 x 624 kW_e	Min output 50%
	Wind turbine	800 kW_e	
	Electricity Network	11kV ring main and 11/0.4kV transformers	Connected to UKPN at 33kV 200kW export limit
	Peak/Min electricity demand	1600 kW_e/800kW_e	
Heat	CHP unit recovered heat	2 x 832 kWt	Min output 50 %
	Gas boiler	4 x 2.5 MWt	
	Hot water distribution circuit		Operated at 90°C/70°C supply and return temp.
	Peak/min heat demand	6000kW_{th}/400kW_{th}	

The site energy management system controls on-site energy assets to meet electricity and heat demand on-site with the aim of minimising site energy costs and maintain reliable and secure energy supplies. It was agreed with estates officers the primary objective of the site operation is for cost minimisation.

4.2 Decision support tool overview for QEH

The decision support tool provides access to and user interactive visualisations of:

a) A high-level overview of the technical and commercial arrangements for energy supply at the campus
b) Historical energy monitoring data and analysis collated from the site at half hourly/hourly granularity
c) Modelling and optimal operation comparison with historical to analyse cost and carbon saving opportunities

Figure 5 illustrates an overview of the key features of the decision support tool developed for the QEH. This has been demonstrated and tested by the estate's energy officers at QEH.

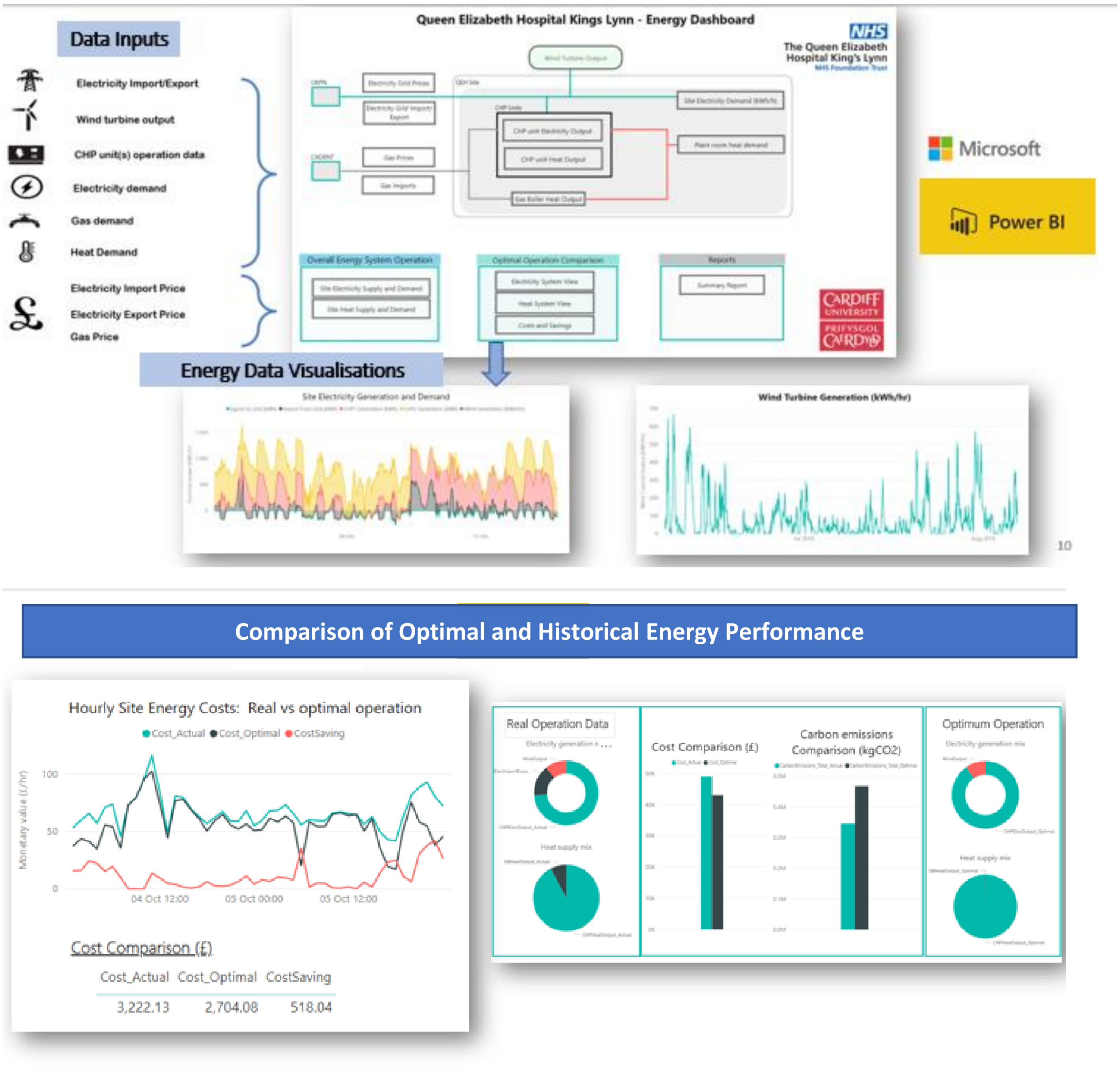


Figure 5: Overview of the decision support tool user interfaces

The data is managed in Microsoft Excel spreadsheets for useability by estates managers whereas the mathematical modelling is based in MATLAB software. The user interfaces were developed in Microsoft PowerBI to read data from excel spreadsheets and facilitate data visualisations and interactive user engagements.

4.3 Historical Operational data analysis and Key Insights

4.3.1 Electricity demand behaviour analysis

The site electricity demand at QEH was calculated using the following formula.

$$P_d^{Elec} = P_{CHP1}^{Elec} + P_{CHP2}^{Elec} + P_{WT}^{Elec} + P_{Im/ex}^{Elec} \quad \text{Equation 1}$$

Where,

- P_d^{Elec}-Electricity demand on site
- $P_{CHP1}^{Elec}, P_{CHP2}^{Elec}$ – Electricity output from CHP1 and CHP2.
- P_{WT}^{Elec}- Electricity output from wind turbine
- $P_{Im/ex}^{Elec}$- Electricity imports/exports (positive if importing, negative if exporting)

Electricity demand at QEH fluctuates between 750kW and 1,600kW and shows a weekly pattern as show in Figure 6

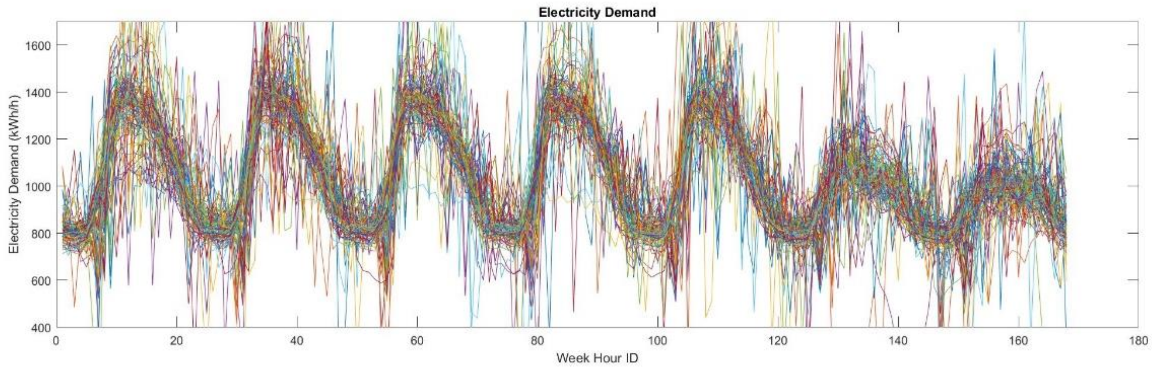


Figure 6: Weekly electricity demand profiles plot for Queen Elizabeth Hospital (Hourly Data from 2019-09-01 to 2020-8-31)

The weekday site electricity demand profile shows a regular pattern whereas the weekend days show a comparatively reduced peak load. The weekday and weekend profile in different seasons has noticeable differences and is analysed separately in Figure 7 to identify the variability in hourly electricity demand.

A base electricity load of around 800kW is observed for both weekdays and weekends in summer and winter seasons.

During winter,

- *weekdays* the demand starts to steadily increase from around 7am to 10am to reach a peak demand of around 1400kW (mean value) which stays stable till around 4pm and starts to reduce gradually until mid-night.
- *weekend* days the demand increase from 7am to 10am to reach a peak demand of around 1000kW (mean) which again stays stable till around 4pm and starts to reduce gradually till mid night.

During Summer,

- the weekday profile shows a similar pattern to the winter weekday profile however with more variability in data. This is likely due to the operation of HVAC units for cooling.
- the weekend profile is somewhat like the summer weekday profile and shows more variability, this is again likely due to the increased cooling requirements of the hospital during summer period and the operation of HVAC units.

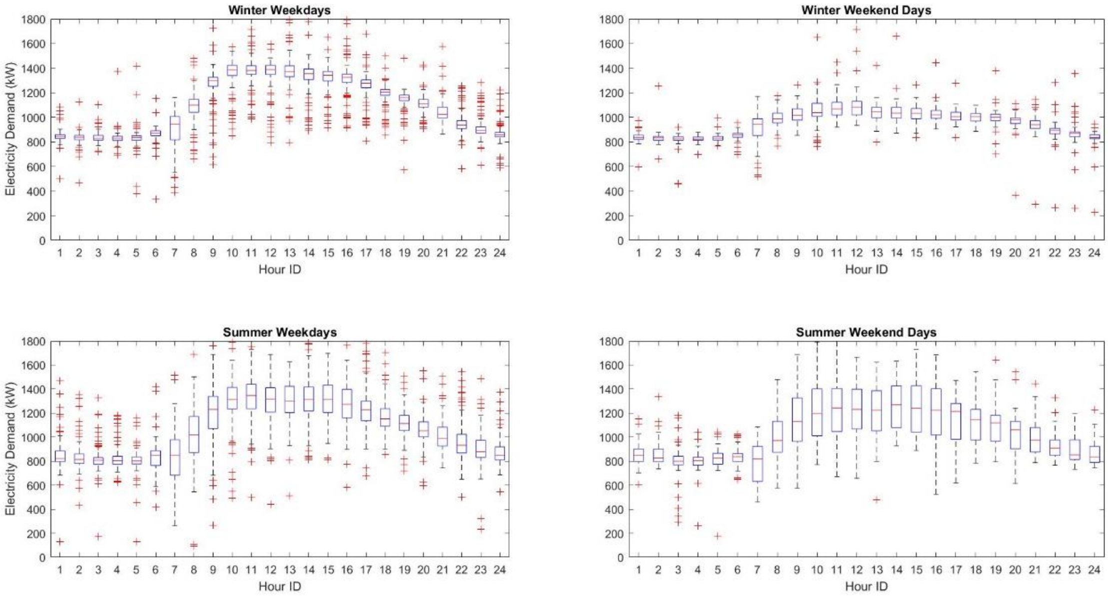


Figure 7: Seasonal and weekend, weekday variation of site electricity demand

4.3.2 Heat demand behaviour analysis

Hourly Heat metering data was available at the output of the 2 CHP units, the 4 Gas Boiler plants and the different plant rooms supplying heat to different parts of the hospital complex for the months of August, October, November, and December 2019. However, not all heat demand areas are monitored across the hospital. Heat dumped at the 2 CHP units are also monitored although the data was shown to be not reliable. The aggregated heat generation data and the aggregated heat metering at the plant rooms (heat demands) are shown in Figure 8.

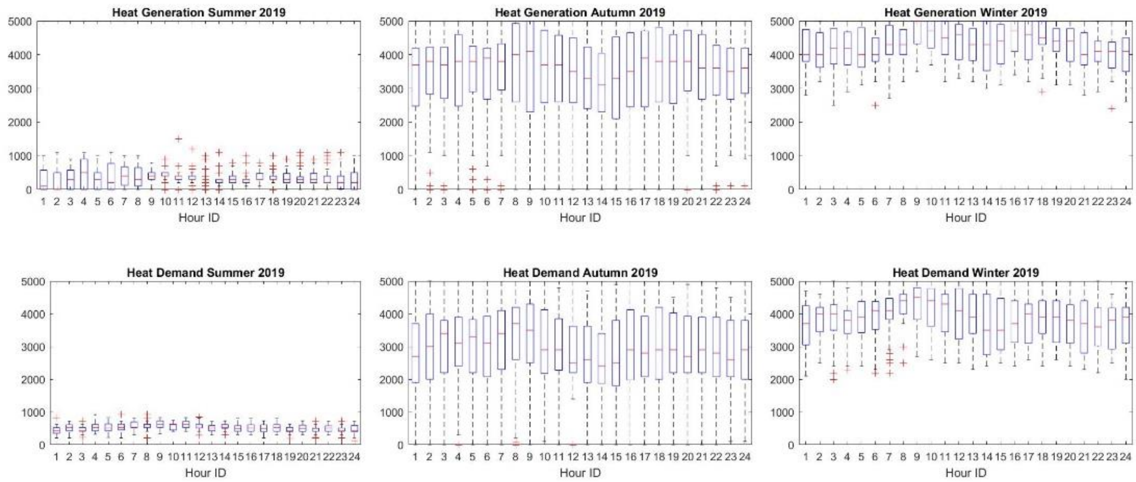


Figure 8: Heat generation and heat demand data for months of August, October, November, and December 2019

As anticipated the aggregated heat generation and heat demand shows an increase from summer period to autumn to winter. This is likely due to the increasing space heating requirements of the hospital complex as the outdoor air temperature reduces.

During the month of August 2019 (summer period);

- the aggregated hourly heat generation and heat demand data varies between 0-1000kWh/h.
- this likely represents the hot water requirements during summer period as there is little/no space heating requirements

During the month of October and November 2019 (autumn period);

- the hourly heat generation and demand have increased and varies between 2000 and 5000kWh/h.

- the data shows significant variability in heat generation and demand throughout the day
- heat generation data shows an overall higher estimate than metered heat demand and this is likely due to system losses and missing heat demand metering points in the system
- no clear predictable daily heat demand pattern can be observed

During the month of December 2019 (winter period).

- the hourly heat generation and demand values are highest during winter period varying between 2000 and 5000kWh/h.
- Like the autumn period data heat generation and demand shows high variability and no clear pattern can be observed for the daily heat demand profile.

Due to the missing heat demand metering points, the aggregated heat generation data will be used to represent the site heat load.

4.3.3 Electricity and heat demand coincidence

Figure 9 shows the frequency of electricity and heat load coincidence for the months of august (summer), October and November (autumn) and December (winter) plotted separately.

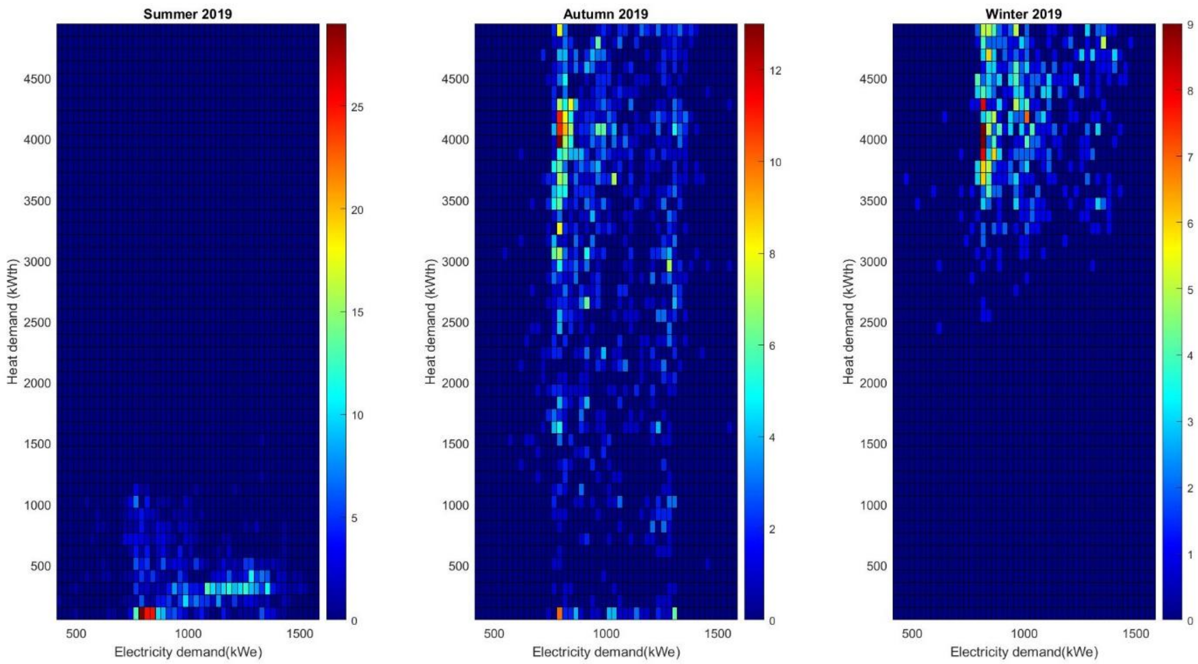


Figure 9: Electricity and heat demand coincidence

The figures show the clear shift in site heat load during different seasons. It also shows that most frequent electricity and heat load coincidences occur at the lower end of site electricity load (~800kW) in all seasons.

4.3.4 Wind generation data analysis

Half hourly wind generation data was available from supplier billing records for the same period. The data was converted to an hourly average value to match with other data available.

The wind generation data was categorised as,

- High wind days –daily mean wind generation was above 540kW (1.5% of the days for the 2-year period)
- Mid-High wind days – daily mean wind generation was above 360kW and less than 540kW (4.1% of the days for the 2-year period)
- Mid-Low wind days - daily mean wind generation was above 180kW and less than 360kW (17.4% of the days for the 2-year period)
- Low wind days - daily mean wind generation was below 180kW (77% of the days for the 2-year period)

Figure 10 shows the hourly wind generation data variation for the 4 categories described above.

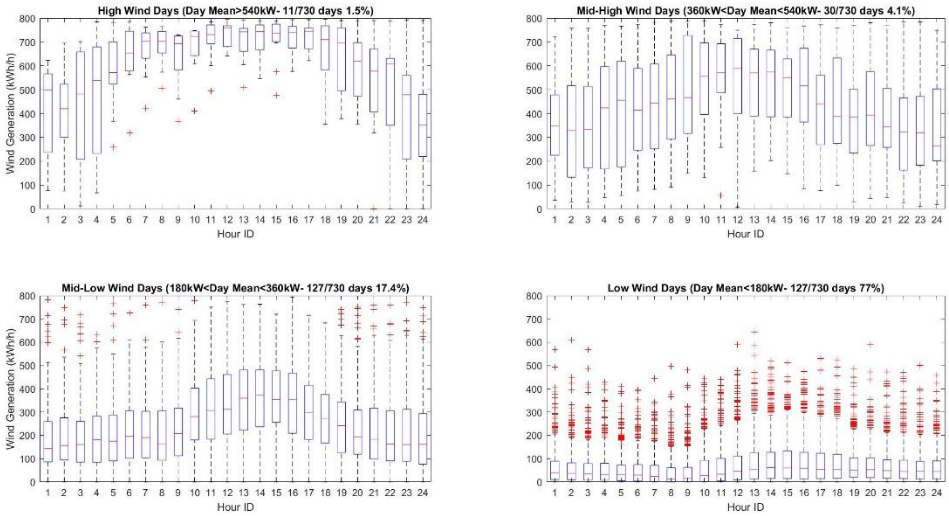


Figure 10: Hourly wind generation data at QEH

There is significant variability in wind generation at the site as observed from the data analysis.

4.3.5 Energy prices

Understanding of energy prices applicable to the site is important for site operation optimisation. This site had a peak and off-peak electricity import tariff whereas the electricity exports received renumeration based on the national grid balancing price which is determined in real time.

Figure 11 shows the electricity import and export price profiles applicable for this site.

A statistical analysis shows that peak export prices tends to overlap with the peak electricity import price periods which is between 16:00 - 19:00 hrs

Gas price is relatively significantly lower and stay constant throughout the day and across seasons.

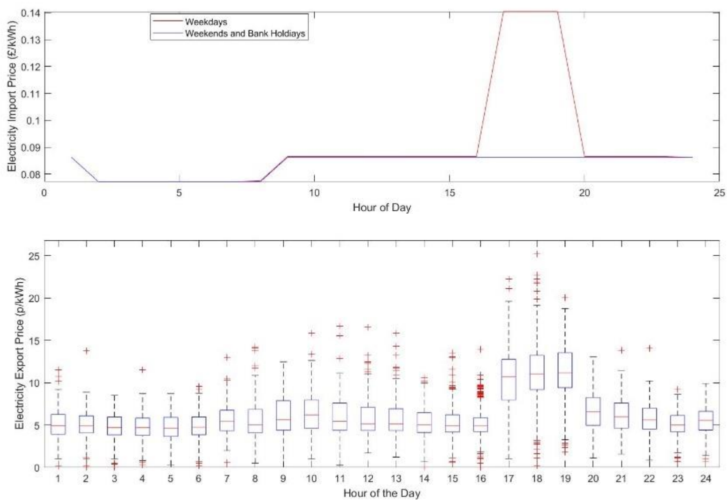
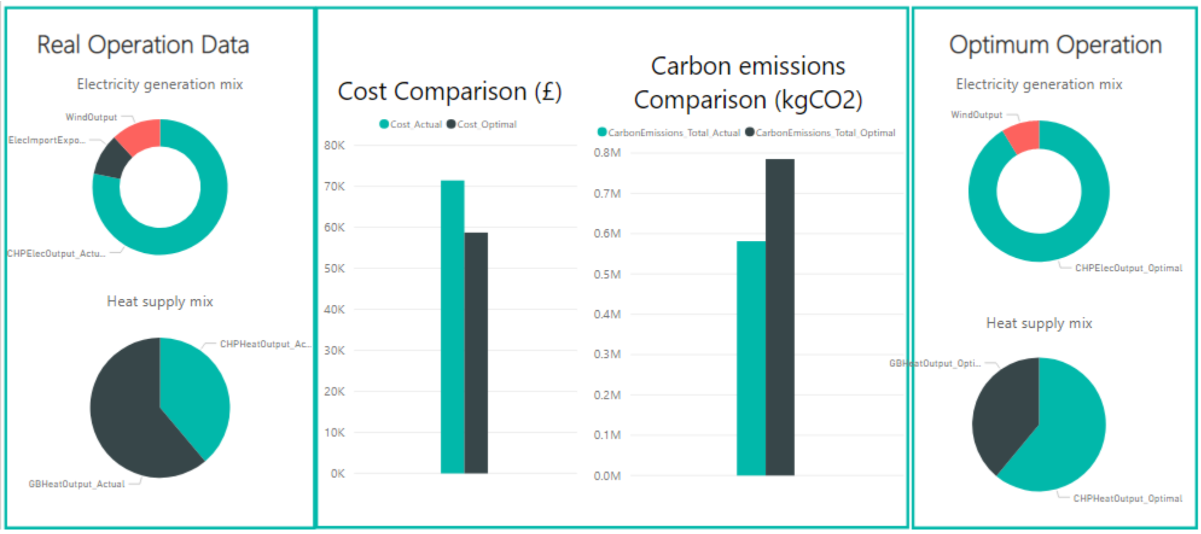


Figure 11: Electricity import and export price profiles applicable for the site

4.4 Operation cost saving opportunity and impact on carbon emissions

The historical energy monitoring data is used for running optimisation studies and to quantify the potential cost saving opportunities available.

Figure 12 shows the decision support tool visualisation to demonstrate the cost saving opportunity and the carbon emissions impact during the month of October 2019.



Cost Comparison (£)

Cost_Actual	Cost_Optimal	CostSaving
71,421.94	58,713.44	12,708.50

Carbon Emissions Comparison (kgCO2)

CarbonEmissions_Total_Actual	CarbonEmissions_Total_Optimal
581.33K	785.04K

Figure 12: Visualisation of potential cost and carbon saving for the month of October 2019

The results show that the electricity imports could have been completely avoided by controlling the CHP generator to better predict electricity demand. The cost saving opportunity was around £12k over the month however it should be noted that this would come with an increase in carbon emissions due to the higher utilisation of the CHP units.

Figure13 shows a monthly breakdown of the potential energy cost saving at QEH found from modelling and optimisation as described in section 2.1. The figures compare optimisation results with real operational data available from the site.

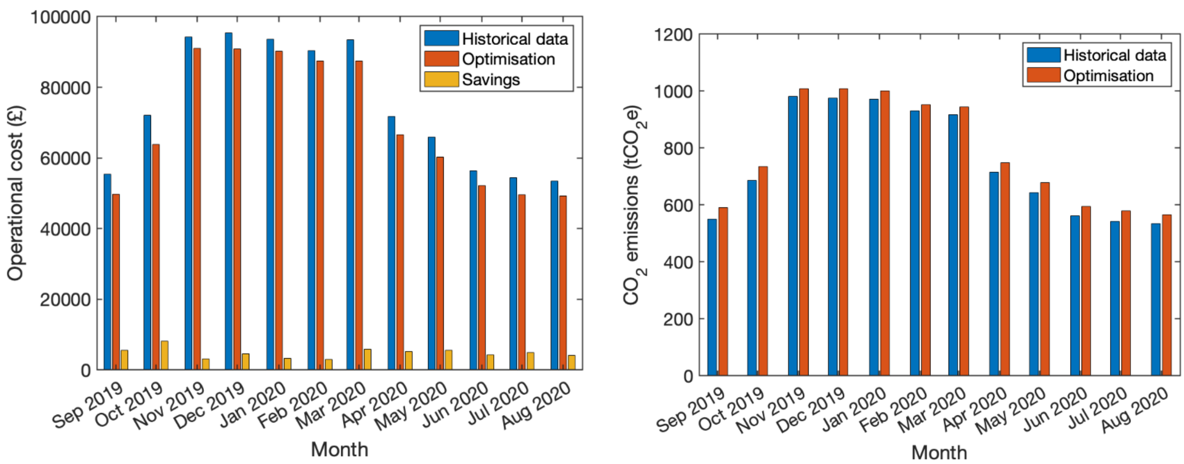


Figure 4: Monthly breakdown of the energy cost saving opportunity and carbon impact

This highlights to the owner that by implementing a change in control strategy for the CHP generator units there is a significant operational cost saving (around 12% overall) that can be realised. This will not require significant capital expenditure and can likely be achieved by a revision of control strategy of CHP generators and additional information on electricity prices and weather being communicated to the control systems. However, this leads to higher carbon emissions on-site due to the increased utilisation of the gas fired CHP generator and presents a dilemma for the operation optimisation.

5 Conclusions

The UK governments' NetZero ambition and the wider power system challenges are driving campus energy systems particularly in public sector to reduce individual carbon footprint by investing on renewable generation, low carbon heating and energy storage technologies.

The public sector faces significant challenges to deliver on its Net-Zero carbon ambitions. There is a clear need for decision support tools and for further support to identify opportunities for improvement of public sector energy systems

Good quality energy data collection, management and analysis is an important area in campus sites that needs improvement in the immediate term. Historical energy data analysis provides valuable insights on the campus site behaviour and will lead to identifying significant opportunities for operation improvement prior to further capital investments.

A simplified mathematical model of a campus site can be developed using historical data and with an understanding of technical structure and commercial arrangements of the site energy system. The mathematical model allows the site owner/operator to evaluate operation improvement options for the site considering their cost and carbon implications.

Natural gas fired CHP generation units are still a popular technology for campus sites to meet on-site electricity and heat requirements. They are economically attractive but is a source of carbon emissions and may delay NetZero ambitions of a campus site. This presents a dilemma for estate energy managers on the continued use or future investment in combined heat and power generation technology. Policy interventions are required so that carbon savings and cost saving technology options are not conflicting options for a public sector energy manager.

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