MODELLING AND EVALUATION OF MULTI-VECTOR ENERGY NETWORKS IN SMART CITIES

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ABSTRACT In an urban context, energy demand growth and the rapid rate of technological change are already having an impact on our energy systems. Considering global ambitions to reduce carbon emissions and minimise the rate and impacts of climate change, this demand will need to be met with energy from low carbon sources. Increased electrification of heat and transport networks is anticipated, however, the cross-sectorial impacts of different interventions in these systems must be better understood to prevent gains in one system leading to losses in another while ensuring financial benefits for producers and consumers. As such, evaluating the impacts of specific interventions can be a challenge, with analyses typically focussed on individual systems. In this paper, a simulation environment is developed to capture the behaviour of interconnected heat, power and transport networks in an urban environment to act as a 'digital twin' for the energy systems of a district or city. The modelling environment illustrated here is based on the smart city interventions of Greenwich in London, with model validation carried out using real data measurements. Building retrofit and heat electrification interventions are demonstrated in terms of costs, energy consumption and CO_2 emissions, considering constraints on power and thermal systems.

1. Introduction

Globally, cities are responsible for 60% of present day GHG emissions and waste (United Nations), accounting for 67-76% of energy use (Edenhofer et al., 2014). Furthermore, current projections indicate that approximately 66% of the world's population will be urban by 2050, growing from 54% in 2014 (United Nations Department of Economic and Social Affairs Population Division, 2014). Significant efforts have emerged to reduce the environmental impact of cities across all sectors, with the energy sector playing a key role. The above statistics speak to the scale of the challenges ahead, however, the high energy densities and diverse demand profiles also provide opportunities for technological innovation (Lund et al., 2014; Zhou et al., 2016).

Within the wider 'Smart City' context, the concept of 'Smart' energy has gathered momentum in recent years, with digital communication technology and computational intelligence providing the means to increase the integration and coordination of lower carbon energy sources. While the benefits of integrated energy networks have been widely reported (Mancarella, 2014; Shah and Keirstead, 2013), assessing the impact of individual interventions on the whole system can be a challenge. Suitable choices of technologies and operating strategies are contingent on quantified benefits (economic, environmental or otherwise) across all energy vectors. With increased electrification of heating and transport for example, a large-scale building retrofit may not only reduce heating requirements, but also reduce the peak electrical load of the system, thus enabling a greater penetration of electric vehicle charge-points. Evaluating the impact across all systems may be crucial to the selection of appropriate technology and the development of strong business cases. Predicting the multi-vector behaviour of the system requires a modelling platform that can capture the interactions of heating, transport and local generation networks.

A wide range of modelling tools are currently available to decision makers. A summary of suitable tools to model renewable energy integration is provided in (Connolly et al., 2010) for example, while approaches for modelling district-scale energy systems are reviewed in (Allegrini et al., 2015) with a further classification of energy system models provided in (Hall and Buckley, 2016). Suitable modelling approaches depend on several factors, including desired time-scale (seconds to decades), technology, hierarchy level (e.g. country-wide, district-level or component level). Design decisions and operational decisions also require different modelling approaches. As the electrification of heating and transport systems becomes more prevalent, the interactions between different system components increases. From a modelling perspective, a challenge then arises, in that a modelling platform must capture the interactions while maintaining the level of detail required to simulate the behaviour of the individual components. The effective simulation of building energy demand for example, requires dynamic modelling tools such as EnergyPlus (DOE, 2017), to accurately capture heat transfer through building fabric. District level simulation tools tend to simulate operation only

for a given set of energy demands however (Connolly et al., 2010), and often neglect lower level components.

Building on work carried out for the EU Horizon 2020 funded Sharing Cities project (www.sharingcities.eu), this paper details the development of a modelling framework that can capture both the detailed thermal dynamics and the technological diversity present in a district level smart energy system and illustrates its efficacy through application to the real Smart City environment of Greenwich. The platform, referred to henceforth as the "digital twin" of the real system, consists of various modelled components (both thermal and electrical) including local photovoltaic solar generation, electric vehicle charge stations and a large social housing unit along with its associated heating network, which includes boilers, water source heat pumps and thermal storage. Furthermore, the digital twin incorporates the Sustainable Energy Management System (SEMS) developed for the Sharing Cities project, which enacts a set of advanced control algorithms to enable optimal operation of the various interacting sub-systems. All components are simulated within the same co-simulation environment incorporating interactions between systems. The platform is designed to be transferable to any urban energy management context using only open-source software. This ability to scale to different problems taking into consideration both high-level system constraints and low-level physical constraints, while capturing the interactions between the different subsystems makes it a novel and relevant framework for design, analysis and evaluation.

The paper first outlines the Greenwich energy systems considered here. Following this, the software architecture of the digital twin is illustrated. The validity of the twin is then established by comparing the simulated outputs with measured data taken from the real systems, showing a high degree of accuracy across several months of data. Following this, a set of case studies are carried out to investigate the impacts of different Smart City-type interventions in the system. More specifically, the interconnected impacts of building retrofit, heat electrification and renewable generation are quantified in terms of economic and environmental and factors.

2. Smart energy landscape – Greenwich

As one of three lead cities in the Sharing Cities project (SHARING CITIES), a wide range of interventions are underway in London, specifically focussed in the borough of Greenwich. These interventions include increasing the electrification of heat and transport networks, implementing additional renewable generation and retrofitting part of the social housing stock. The multi-vector nature of the interventions makes Greenwich a suitable case study for the developed simulation platform framework. The interventions captured in the modelled case study are summarised in this section.

2.1 Energy system assets

The Ernest Dence estate (shown in Figure 1) is located near the south bank of the River Thames in Greenwich. Consisting of the 95 apartments, ranging in size from 2-5 bedroom, the estate is used for social housing by the Royal Borough of Greenwich (RBG). Space heating is provided by gas boilers, with an average annual gas consumption (measured between 2009 and 2013) of approximately 2 TWh, which amounts to 370 kWh/m^2. This greatly exceeds the average figures for the UK (Department for Business Energy & Industrial Strategy, 2018). To reduce the energy consumption and the reliance on gas, a retrofit is to be carried out. Roof insulation is to be improved while the network of piping associated with the heating system is to be redesigned to reduce heat losses.

Figure 1: The Ernest Dence estate

Water source heat pumps (WSHP) with a combined capacity of 400 kW are to be used to supply heat to the estate using the Thames as the heat source while the heating system operating temperature is to be lowered, necessitating a redesign of the buildings radiators. Lower temperatures ensure more efficient WSHP operation as well as reduced heat loss from the pipes. Water tanks with a total capacity of 6 m^3 will also be available for thermal storage, while additional boilers will be used only when required as a back-up heat source.

Aside from the Ernest Dence estate, solar PV panels are to be installed on the roofs of several other social housing blocks in the Greenwich area with a combined capacity of 270 kWp. Furthermore, a shift in transport in the Borough towards greater penetration of electric vehicles will be facilitated by the installation of EV charge stations.

2.2 Sustainable energy management system

The applications of the previously outlined interventions differ, with transport, heating and generation all represented, however, the presence of heat network supplied by an electrically powered heat pump indicates that the systems can be seen to interact through the power network. These interactions must be considered at the district level. If peaks in the power drawn by the EV charge stations coincide with peaks in the heating requirement for example, the local electricity grid may become over-stressed. On the other hand, the flexibility provided by the heating network through the presence of thermal storage (including the water tanks as well as the storage associated with the large thermal mass of the

apartment block itself) allows for temporal shifting of the electrical loads. With appropriate management, coinciding peaks can then be avoided. Furthermore, variable energy prices and grid carbon intensities can be exploited to minimise energy use at times of high price or high CO_2 intensity, or maximise the local use of renewably generated power. To handle these considerations, a Sustainable Energy Management System (SEMS) has been developed for the Sharing Cities project.

To succeed as a tool for design, analysis and evaluation, a digital twin of the energy landscape must be able to incorporate all outlined system components within a single platform, capturing interactions between components while allowing advanced control and optimisation-based strategies to be simulated.

3. Simulation environment – the digital twin

3.1 Architecture of digital twin and SEMS

To handle the range of potential energy components within a single framework in an open-source manner while allowing for co-simulation with different modelling software, the Building Controls Virtual Test Bed (BCVTB) (Simulationresearch, 2016) in the Ptolemy II framework (Eker et al., 2003) was chosen as the central modelling environment. The actor-oriented design of Ptolemy II allows different components to execute concurrently, suiting the modular nature of a multi-scale energy system, while BCVTB enables coupling with other software packages. Furthermore, the platform can be allowed to communicate with an external set of control algorithms through a web application framework. A high-level schematic of the information flow between different software components is illustrated in Figure 2. By simulating all sensor measurements present in the proposed real system, it should be possible to design the control algorithms using the digital twin and simply swap out the twin for the real system after sufficient testing and analysis has been carried out, though control aspects are not the focus of this paper.

Figure 2: Information flow in digital twin
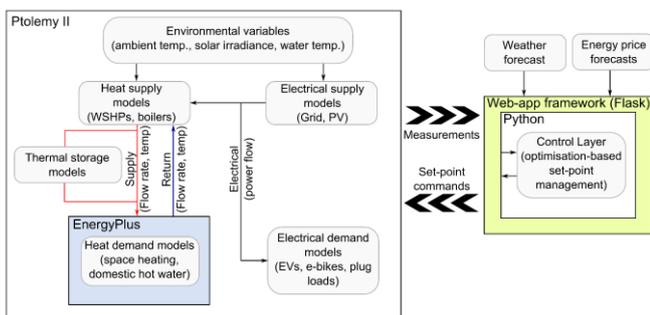
3.2 Modelling Greenwich systems

In the Greenwich case, the digital twin is composed of a heating network (with boilers, heat pumps and thermal storage), the apartment block it supplies, EV charge stations and PV panels. External temperatures, solar irradiance profiles, energy prices and EV charger loads are included as

time-series actors. The heat pumps, boilers, thermal stores and low-level controllers and valves are modelled by standard heat transfer and mass balance equations, implemented using standard Ptolemy mathematical actors, logic blocks and look-up tables. The thermal dynamics of the apartments are modelled using the state-of-the-art building modelling software EnergyPlus (Crawley et al., 2000). Taking work initially carried out in (MOEEBIUS), the dimensions, materials and radiator system design of the Ernest Dence estate are used to develop a high-fidelity model in EnergyPlus (the physical model is shown in Figure 3).

Figure 3: Representation of the modelled Ernest Dence estate
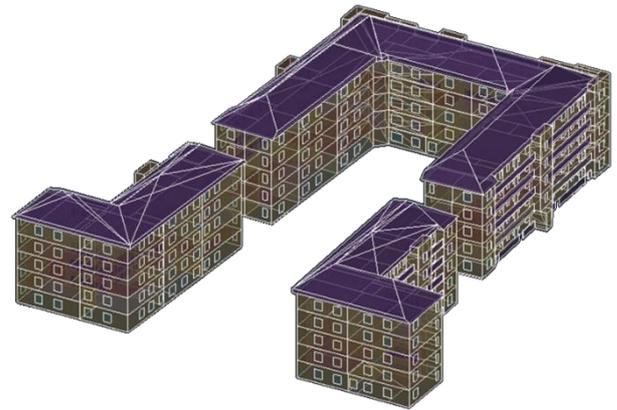
Heating system supply temperatures and system set-points are passed from the Ptolemy-based heating system model to the EnergyPlus model, while room temperatures and system return temperatures are passed back. The top level of the digital twin graphical user interface is shown in Figure 4.

Figure 4: Top-level of the user interface of the digital twin
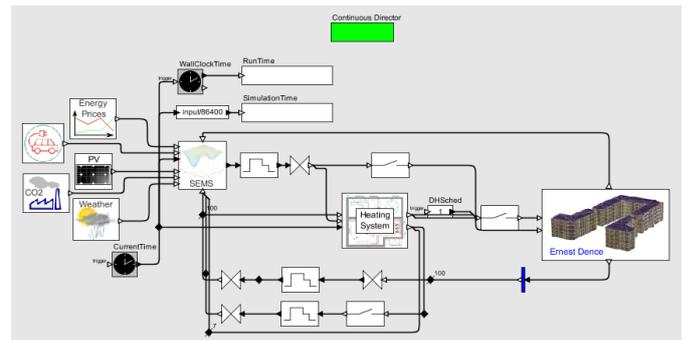
All sensors planned for the real system are present in the digital twin with measurements passed to the control layer via a web application framework (Flask, 2014). The python-based control layer calculates an optimal set of operational set-points which are then passed back to the digital twin at a chosen sample time (15-minute samples are typically used here).

3.3 Validation of model accuracy

As previously stated, one of the key advantages of having a simulation environment is the ability to analyse different scenarios prior to implementation in the real world. As such, it

can be a challenge to validate the accuracy of the modelled components with real data, given that the real-world components may not yet exist. While this is true in the case of most of the energy system components in this Greenwich case (such as the heat pump), perhaps the key component – the Ernest Dence estate itself – does exist, though in pre-retrofit form. Half-hourly gas consumption measurements are available for the full estate, which allows a comparison to be made between the digital twin and the real system. Using the pre-retrofit building and heating system parameters (with only boilers as the heat source) a 50-day simulation was run to emulate the period from the 09/02/2018-30/03/2018 using weather data for the same period taken from (timeanddate.com). The external temperature profile for the period is shown in Figure 5

Figure 5: External temperature in London during modelled period
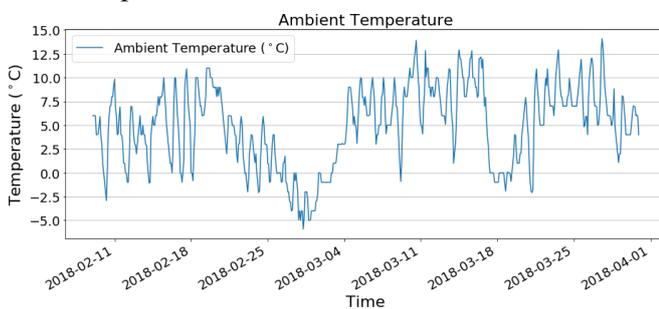
Simple assumptions were required to generate occupancy profiles and internal radiator set-points as this level of data was not available. Inevitably, differences will arise between any such assumptions and the reality of the hour-to-hour and day-to-day lives of the residents, particularly relating to how they interact with radiators and windows. Nonetheless, broadly assuming an averaging-out over time of such differences, it should be possible to observe the relationship between the external conditions and the energy consumption. To see this, for the full 50-day period, the gas consumption predicted by the digital twin is compared here to the actual gas consumption as measured in the estate. This is shown in Figure 6 where the solid line indicates the measured data, while the dashed line indicates the consumption predicted by the model. A 40-hour period during which an apparent fault in the real data measurements can be seen, starting on the 25/02/2018. Apart from this, the heating profiles show strong similarities in terms of both the seasonal and daily variations, with the expected inverse relationship to the external temperature clearly visible in both.

Figure 6: Measured vs modelled heat requirement of Ernest Dence estate
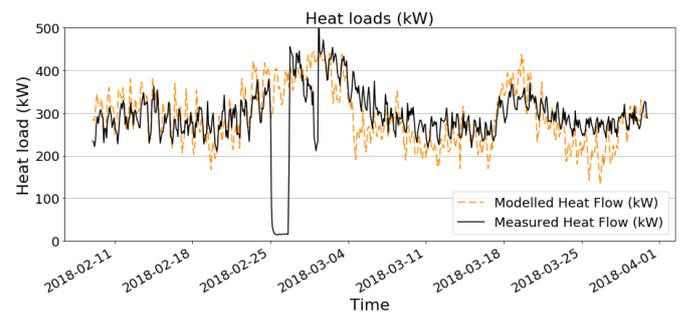
Removing the data-points associated with the 40-hour fault period from both profiles, the total gas consumption is shown for the remaining measured and modelled data in Table 1. With a heat underestimation of just 3.1 %, the model was successful in predicting the heating requirement of the building.

Table 1: Measured vs. modelled gas consumption in Ernest Dence estate over un-faulted period

|	Measured (MWh)	Modelled (MWh)
Gas Consumption	346.7	335.8

4. Evaluating interventions

4.1 Building retrofit – Gas boilers

To improve the energy performance of the estate, a retrofit is to be carried out by the council, in which the roof loft insulation is to be increased. Currently, 150 mm depth insulation is present. This shall be increased 300 mm to achieve a U-value of 0.13 W/m^2 or better. To simulate this, the parameters associated with the roof insulation were modified appropriately in the EnergyPlus model.

The radiator pipework and heat network are also to be redesigned and reinstalled to reduce heat losses to the environment and to unheated zones in the estate. The length of the pipework is to be significantly reduced through better routing, while improving the insulation of the pipework and reducing the pipe diameter should all lead to reductions in unwanted heat transfer from the pipes. Once again, the relevant parameters in the model were modified and the digital twin was run for the same 50-day period once again. The energy consumption predicted by the model before and after the retrofit interventions is shown in Figure 7 where the solid line represents the modelled heat load before retrofit, while the dashed line represents the heat after the retrofit.

Figure 7: Modelled energy consumption before and after retrofit activities
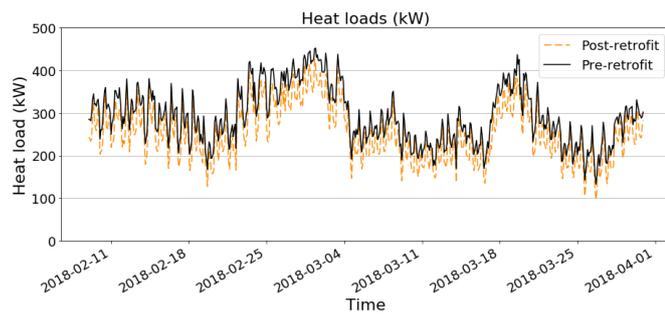
The resulting impact of the retrofit is evaluated in terms of CO_2 emission and fuel cost in Table 2. It was assumed that the gas boilers operated at 78 % efficiency (the boilers are quite old), while a gas cost of 18.3 c/kWh is used. A value of 0.184 $kgCO_2$/kWh is assumed for the CO_2 intensity of natural gas, taken from (Department for Business Energy and Industrial Strategy, 2018). With these data, an energy consumption reduction of 12.8 % is predicted in the 50-day simulation period after retrofit interventions had taken place. This corresponds to a decrease in fuel costs of more than £1000, with a reduction in CO_2 emissions of more than 10 tCO_2. From a decision-maker's perspective (in this case, local government), the capital costs, both in terms of money and CO_2, of the interventions can be weighed against these quantified operational benefits, enabling more informed decisions to be made about the worthiness of any retrofit interventions.

Table 2: Predicted gas consumption of Ernest Dence estate before and after retrofit interventions

	Pre-retrofit	Post-retrofit
Gas Consumption (MWh)	449.4	391.9
CO_2 emission (t)	82.7	72.1
Fuel cost (£)	8224	7172

4.2 Impact of heat electrification in district – Water source heat pumps

Given the reduction in CO_2 intensity of the UK's electricity grid in recent years (HM Government, 2017) and the potential to exploit high Coefficients of Performance (COPs), shifting the burden of heating from gas boilers to heat pumps has the potential to greatly reduce the environmental impact of the heating sector. With this in mind, a further intervention to be implemented in Greenwich is the installation of a water source heat pump to replace the current aging centralised boiler system in the Ernest Dence estate. A hybrid system is to be established in which four heat pumps with a combined capacity of approximately 400 kWth (depending on the source temperature) are to be used, with an additional set of boilers to be installed as a backup, to be used when the energy demand exceeds the installed heat pump capacity. A lower heat network temperature set-point of 60 °C is to be used to ensure that a favourable heat pump COP is achieved. This will require the installation of larger radiators in the apartments to allow for adequate heat transfer between the radiator and the air, given the reduced temperature difference between the two. Two thermal stores of 3 m³ each are also to be installed as a buffer.

The new system components were modelled in the digital twin with a simulation run carried out once again for the 50-day period. The COP of the water source heat pump is assumed to reduce from 3.5 to 2 as the source (the river) temperature decreases from 20 °C to 4 °C (based on monthly average river temperatures measured at Littlebrook Power Station). A simple on/off hysteresis-type strategy is used to control the output of the heat pump. If the return temperature of the heat network falls to more than 2 °C below its set-point, the heat pumps switch on until the network temperature rises back above the set-point, at which point they switch off again. In times where the heat pump capacity is insufficient, the network temperature will continue to drop, in which case the back-up boilers switch on as a supplementary supply.

Using this operational logic, the performance of the gas boiler system is compared to that of the proposed heat pump (in both cases it is assumed that the previously described insulation and pipework retrofit interventions have already taken place). A two-tier electricity tariff is assumed for the apartments, with a day tariff of 10.7 c/kWh and a night tariff of 6.6 c/kWh. The CO_2 intensity of the electricity grid for the period is taken from the National Grid's Carbon Intensity API (Carbon Intensity API) which provides half-hourly values. The resulting performance is summarised in Table 3. In the heat pump-based system, the gas boilers are used infrequently and as such, the gas consumption is greatly reduced. The shift towards electricity introduces a significant decrease in CO_2 emission (63 %), however the cost of supplying the energy has increased by about 9 %. Despite the significant reduction in energy consumption, the relatively high day tariff makes the heat pump more expensive to run when compared with the gas boilers in this case. From this, the operational cost of CO_2 mitigation can be taken as 15.64 £/tCO_2.

Table 3: Operational impact of heat electrification

	Pre-electrification	Post-electrification
Gas (MWh)	391.9	8.1
Electricity (MWh)	0	81.0
CO_2 emission (t)	72.1	26.8
Energy cost (£)	7172	7881

To reduce costs, an alternative strategy can be implemented in which the heat pumps are only run during the night, with the boilers used during the day. Furthermore, the thermal stores can be optimally managed using the SEMS control framework to ensure cost is minimised. This is achieved by charging during the night period using the heat pump and discharging during the day to maximise the exploitation of the heat pumps during the low-tariff periods. The performance of this

approach is summarised in Table 4. Here, the cost is approximately the same the boiler-based system, with a reduction in CO_2 of 25 %.

Table 4:Performance of combined WSHP/Boiler strategy

	Pre-electrification	Post-electrification
Gas (MWh)	391.9	197.7
Electricity (MWh)	0	25.9
CO_2 emission (t)	72.1	53.8
Energy cost (£)	7172	7158

The three different strategies are illustrated in Figure 8 in terms of CO_2 emissions and energy cost. This case is illustrative of the type of trade-off that can commonly be found in the energy sector as competing financial and environmental objectives can produce opposing design decisions, while operational strategies must also be considered. The choice of the 'best' strategy can be subjective. With the use of the digital twin, different strategies can be evaluated quantitively to assist the decision-maker.

Figure 8: Environmental and financial comparison of operational strategies
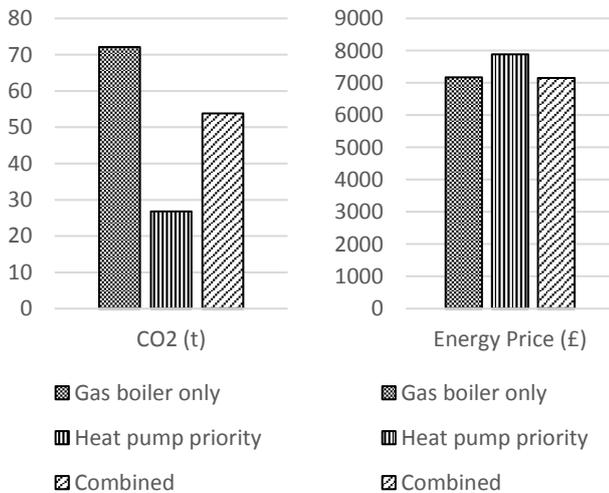
4.3 Impact of renewable PV installation in district
As previously indicated, the borough also seeks to increase the renewable generation in Greenwich through the installation of PV panels. Considering the greater electrical requirement resulting from heat pump-based heating systems, this is a critical initiative. The PV panels are modelled in the digital twin following the approach in (Duffie and Beckman, 2013). Based on the solar irradiance, time of day and the orientation and geographical locations of the panels, the power output from each panel is calculated. Using the heat pump prioritised strategy from Section 4.2, the electrical generation and consumption of the new assets in Greenwich is plotted in Figure 9 for the same 50-day simulation period Consumption

is plotted as in the positive direction, while generation is plotted in the negative direction.

Figure 9: Electricity consumption and generation in new assets
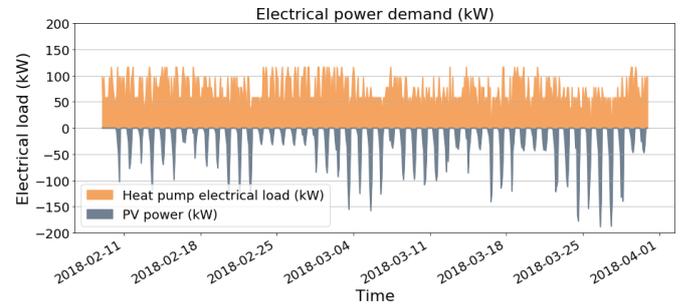
The offset cost and CO_2 achieved by the use of the PV panels is summarised in Table 5. With 270 kWp of installed capacity, the generation of approximately 24.9 MWh electricity was predicted for the 50-day period. With the assumption that the produced power can be consumed locally, this can reduce the electricity import cost by over £2600. Taking all interventions into account, the CO_2 emission from the modelled assets in the borough can thus be reduced from 83 t/CO_2 to 19 t/CO_2 for the simulated period. This equates to a reduction of 77 %.

Table 5: Operational impact of PV installation

	Pre-interventions	Post-interventions
PV generation (MWh)	0	24.9
Offset energy cost (£)	0	2636
Offset CO_2 (t)	0	7.8
Total CO_2 (t)	82.7	19.0
Total energy cost (£)	8224	5245

5. Conclusion

As smart city interventions begin to pervade the urban energy landscape, reliable methods for analysing and evaluating the system-wide impacts of any action is required. Energy networks are becoming more interlinked with the electrification of the heating and transport sectors. Decision makers require transferable tools with the flexibility to be used in different contexts to enable the impacts of design or operational decisions to be quantified. In this paper, a modelling platform, or digital twin, is proposed to capture the interactions between various urban energy systems while incorporating enough detail to rigorously evaluate specific interventions in terms of operational costs and CO_2 emission. The proposed software architecture is first illustrated, with an emphasis on the modular open-source nature of the platform to promote transferability. To demonstrate the use of the platform, the energy systems of the borough of Greenwich are modelled. Model validation is carried out using measured data over a 50-day period. Interventions associated with the H2020 Sharing Cities project that are currently underway in the borough are then outlined, including building retrofit, the

transition of a heating network supply from gas boilers to water source heat pumps and the installation of PV panels. An evaluation of these interventions is carried out using the digital twin in terms of the impact on the operational CO_2 emissions and energy costs. The predicted outcomes of these interventions emphasise the need for both design and operational decisions to be considered in the evaluation process, highlighting the value of the proposed platform.

6. Acknowledgements

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