CESI Flex Fund Project Report

Operation Improvement of Public Sector Multi-Energy Systems

The Case Study of the University of Warwick Energy System

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1 Introduction

The methodology to improve the operation of a multi-energy system entailed the following three steps:

a. The mathematical modelling and optimisation of a campus multi-energy system using an energy hub model to identify opportunities for saving cost and reducing CO_2 emissions of the site operation;
b. The formulation of new control rules for the operation of the CHP generators based on the modelling and optimisation results; and,
c. The use of a Digital Twin of the site energy system to simulate and validate existing and new control rules.

This methodology was demonstrated on the University of Warwick (UoW) multi-energy system.

2 Description of the case study

- Energy system components

UoW is a large campus. The electricity and heat infrastructures on the campus are owned and managed by the university. A simplified schematic of the UoW energy system is shown in the Figure 1. The on-site energy system is connected to an electricity network and a gas supply network. The energy demands being served are on-site electricity demand, building space heating and hot water demand and a space cooling demand. In this research, the space cooling demand was not considered. CHP generators and gas boilers are used to supply the heat and electricity demands of the campus. There is no electricity export agreement.

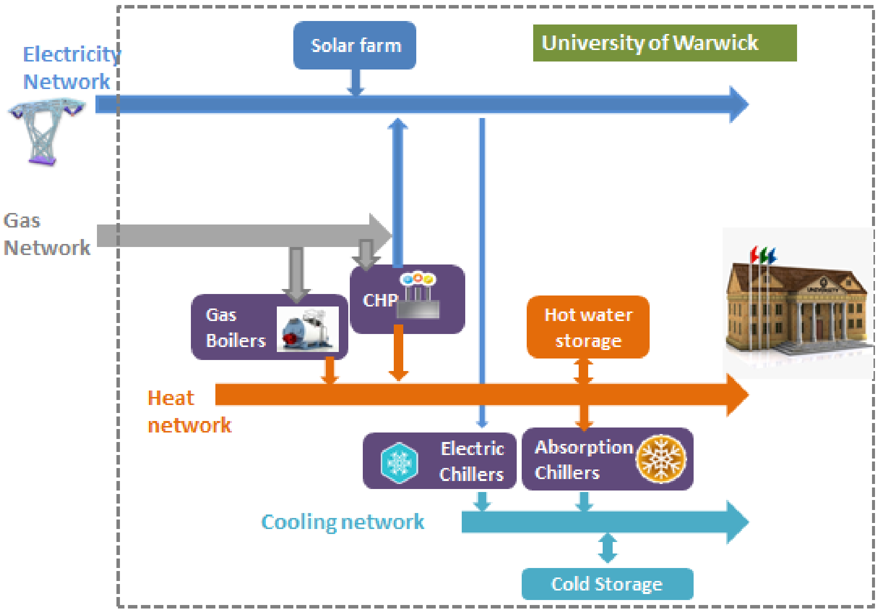

Figure 1. Simplified schematic of the UoW energy system.

The technical details of the main energy supply and conversion units are provided in Table 1. These units are located in two energy centres: the main energy centre (MEC) and the Cryfield energy centre (CEC).

Table 1. Technical details of the main energy supply and conversion units of the two energy centres.

Energy supply and conversion unit		Electrical capacity	Thermal Capacity	Min. operating load
Main Energy Centre	CHP generator 1	1.4 MW_e	1.6 MW_{th}	66%
	CHP generator 2	1.4 MW_e	1.6 MW_{th}	66%
	CHP generator 3	1.4 MW_e	1.6 MW_{th}	
	Gas boiler 1		4.87 MW_{th}	

	Gas boiler 2		4.87 MW_{th}	
	Thermal storage 1		5.81 MWh_{th} (200m^3)	
	Total(generation/storage)	4.2 MW_e	14.54 MW_{th}, 5.81 MWh_{th} (storage)	
Cryfield Energy Centre	CHP generator 4	2 MW_e	2.2 MW_{th}	50%
	CHP generator 5	2 MW_e	2.2 MW_{th}	50%
	Gas boiler 3		5.24 MW_{th}	
	Thermal storage 2		2.9 MWh_{th} (200m^3)	
	Total(generation/storage)	4.4 MW_e	9.24 MW_{th}, 2.9 MWh_{th} (storage)	

2.1 The current control strategy

The CHP generators, thermal energy stores and gas boilers at UoW energy system has a thermal energy demand led operation. The units are dispatched following a merit order table (Table 2). There is no agreement to export electricity thus electricity export is maintained to zero.

Table 2. Merit order for the heat dispatch of the energy supply and conversion units.

Merit order	Name of the unit
1	CEC thermal store
2	CEC CHP generator 1
3	CEC CHP generator 2
4	MBH thermal storage units
5	MBH CHP generator 1
6	MBH CHP generator 2
7	MBH CHP generator 3
8	MBH gas boiler 1
9	CEC gas boiler 3oiler
10	MBH gas boiler (2

The control logic for the heat dispatch operation of the UoW energy system is summarised in Figure 2. The day is divided into 6 x 4 hours intervals of operation (e.g., 2-6am, 6-10am, etc.), the dispatch of the energy supply and conversion units in the UoW energy system is then done following these six steps:

- **Step 1:** At the beginning of each four-hour period the available energy in thermal storage units in both energy centres are calculated. The average temperature of the thermal storage units at the beginning of each four hours period is used as a key input parameter to the calculation.
- **Step 2:** The predicted thermal energy load for a four-hour period is extracted from the lookup Table A. 1 at the beginning of each period (e.g., 2am, 6am, etc.). The outdoor ambient temperature (OAT) at the beginning of each period is measured and used as input to the lookup table.
- **Step 3:** The target for the thermal energy stores at each energy centre at the end of the four hours period is taken from a look-up table (Table 4).
- **Step 4:** The thermal energy output from the CHP generators (if operating at the current power output over the next four-hour period) is calculated in MWh.
- **Step 5:** The calculation to determine the number of CHP generators and gas boilers to operate during any 4-hours period is based on the merit order table (Table 2).
- **Step 6:** This calculation will be repeated on a 30 min cycle, resetting the gas boilers output as required.

The input parameters used by the UoW BEMS are listed in Table 3.

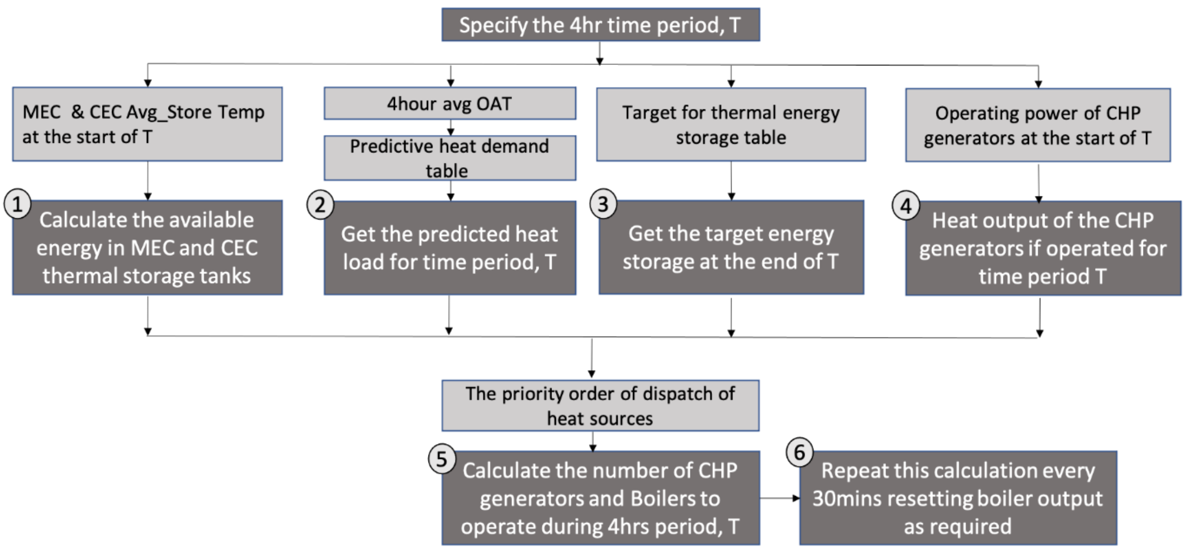

Figure 2. Control logic of the operation of the UoW energy system.

Table 3. Input parameters used in UoW BEMS.

Input parameters	Description
Time period, T	24hours of the day is divided into six 4hour time periods
OAT	4hour average outdoor ambient temperature
MEC Avg_Store Temp CEC Avg_Store Temp	Average temperature of the thermal storage units
The priority order of dispatch of heat sources	Based on the cost of operation and efficiency a priority order of dispatch of heat sources is defined (Table 2)
Predictive heat demand table	A lookup table (Table A. 1) which gives the predictive heat demand based on 4hour average OAT (predictive learning can be enabled)
Target for thermal energy storage table	A lookup table which gives the target energy to be stored in the thermal storage units at the end of each 4hour period (Table 4)
Heat energy output from each unit for 4hr operation	A set of pre-calculated values assuming a full power operation of each heat source for a 4hr period (Table A. 2)

Due to the constraints on the electricity export, the CHP generators will be modulated to avoid exporting electricity back to the UK grid.

Table 4. Lookup table for target thermal energy storage levels.

Time	Target storage level (MWh)					
	Winter		Spring/Autumn		Summer	
	MBH	CEC	MBH	CEC	MBH	CEC
6am	6	3	2.9	1.45	2.9	1.45
10am	1.8	0.9	1.8	0.9	1.8	0.9
2pm	2.2	1.1	2.2	1.1	2.2	1.1
6pm	2.6	1.3	2.6	1.3	2.6	1.3
10pm	2.2	1.1	2.2	1.1	2.2	1.1
2am	2.9	1.45	2.9	1.45	2.9	1.45

2.2 Historical data

For this study historical operational data of the UoW energy system was collected at half hourly resolution for one year period (Jan 2019 – Dec 2019). The data include,

- import from the electricity grid,
- the electricity output from the CHP generators,
- the heat output from the CHP generators,
- the heat output from the gas boilers,
- the heat demand of the site,
- charge/discharge rates of thermal energy storages and their State of Charge (SoC),
- gas and electricity prices.

3 Operation improvement of the thermal storages

The aim of this research was to improve the operation of the thermal storage units to reduce energy costs by providing an update of the lookup table shown in Table 4.
To have a benchmark against which testing the new lookup tables, a digital twin of the UoW was created based on the existing control logic rules. UoW multi-energy system was modelled using the concept of energy hubs. An optimisation of the energy hub model of the UoW was conducted. The results were used to derive new lookup tables that were implemented on the Digital Twin and compared with the benchmark.

3.1 Establishing and validating the Digital Twin using the existing control rules

Several issues were noted regarding the historical metered data of the UoW thus it could not be used directly as a benchmark to assess and compare the changes in operational costs and greenhouse gas emissions accurately. A digital twin of the UoW energy system was developed for this purpose.

Figure 3 shows that the electricity generation from the CHP generators in the UoW in 2019 is reaching zero for a significant number of consecutive days in July, August, and September. This was not expected based on the daily electricity demand and the control strategy of the CHP generators. This may be explained by some errors with the recording of the metered data or some extended maintenance.

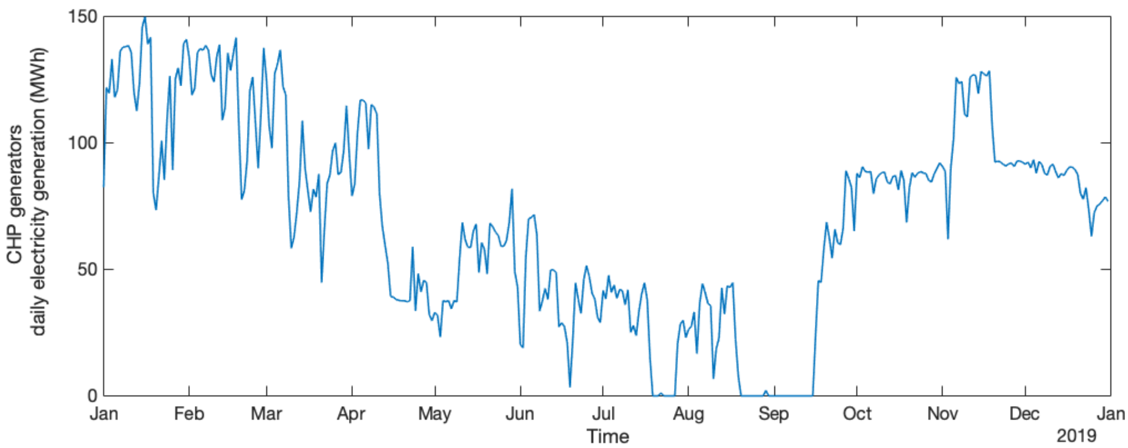

Figure 3: Daily electricity generation from the CHP generators of the UoW in 2019.

Figure 4 shows the recorded hourly energy storage level of the thermal storage units for days in Winter, Summer and Spring/Autumn. There are negative energy storage level values observed. This is not physically possible and may be explained by issues with the heat metering devices of the thermal storage units. The patterns of the average profiles of the thermal storage levels (the red dotted line) are also different from what is expected from the lookup table shown in Table 4 and represented by the green lines. In all seasons, a peak in the thermal storage level is expected to happen in the early morning (2 to 6am) but the profiles are mostly constant over the days except in Winter where a small peak happens at 5am.

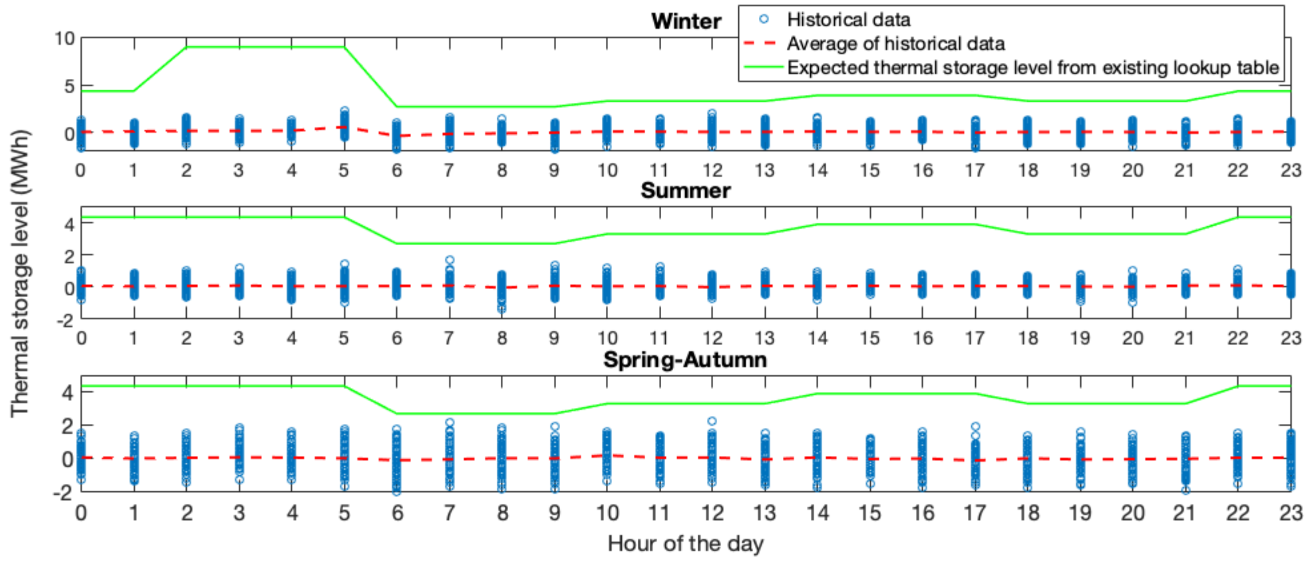

Figure 4: Hourly thermal storage level variation for the days in each season based on 2019 data. The red dotted line shows the average thermal storage level. This was calculated by comparing the heat output from the energy centres with the heat output from the CHP generators and gas boilers.

These issues observed in the historical data about the energy dispatch from the CHP generators and the thermal storage level values led to the development of a digital twin for the UoW that could be used as a benchmark to compare with the optimisation results and test new lookup tables. To limit the changing variables and identify the impacts of the improvements of the lookup table for the thermal storage units the following assumptions were made to build the digital twin:

- The current electricity demand is known;
- The heat demand for the period t and $t + 4\ hours$ are available;
- The outside air temperature is known at all time;
- 2019 electricity and heat demand for the site were used;
- The unavailability of CHP generators, gas boilers due to maintenance or failure are not modelled;
- The CHP generators cannot generate more electricity than the electricity demand of the site; and,
- No heat dump happens to produce more electricity from the CHP generators.

Figure 5 shows the half-hourly heat output from the CHP generators, gas boilers and thermal storage units for a week in 2019. Based on the merit order table (Table 2), the thermal storage units and the CHP generators are dispatched first. The gas boilers are used as peak load units to meet the rest of the heat demand. The heat demand of the site is always met. Heat is dumped when there are large variations of the heat demand within a 4-hour period which leads to over-generation of heat from the CHP generators and gas boilers.

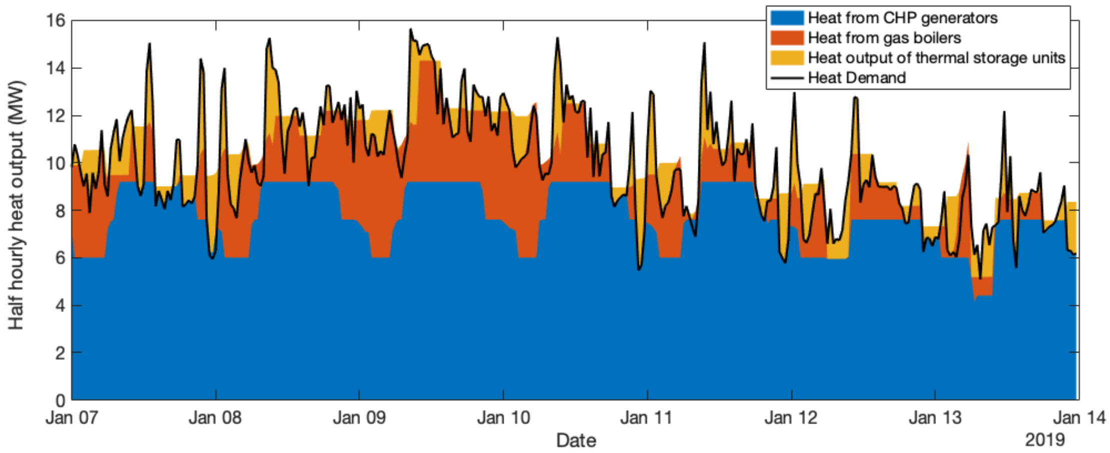

Figure 5: Stacked chart of the half-hourly heat output from the CHP generators, gas boilers and thermal storage units in the second week of January 2019.

Figure 6 shows the hourly thermal storage level for days in the three seasons in the Digital Twin based on 2019 data. The average profiles (red dotted lines) follow closely the lookup table values represented by the green lines.

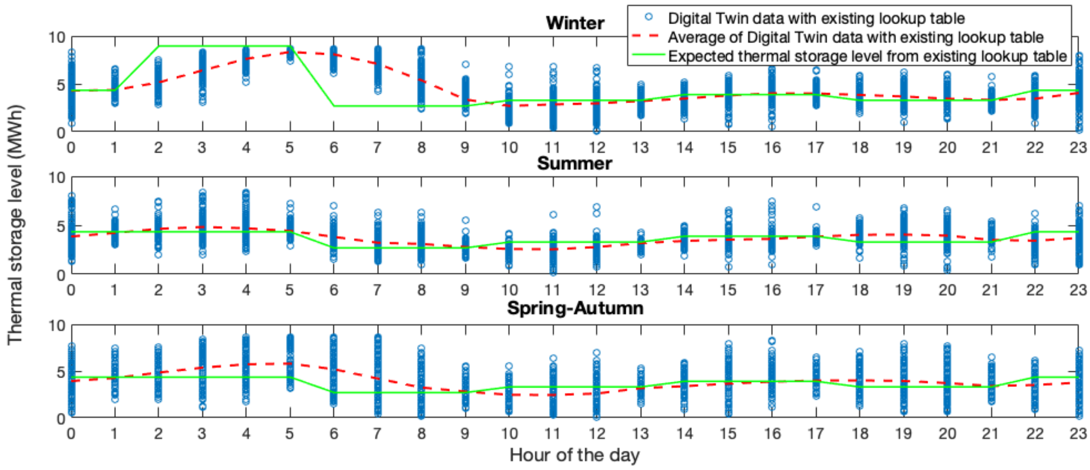

Figure 6: Hourly thermal storage level variation for the days in each season based on 2019 data. The red dotted line shows the average thermal storage level. This was calculated by comparing the heat output from the energy centres with the heat output from the CHP generators and gas boilers.

The Digital Twin mimicked the expected behaviour of the UoW energy system based on the existing control strategy and the lookup table for the thermal storage units described in Section 2.1. The operation data produced using this Digital Twin will be used to assess the potential savings that can be achieved by optimising the energy dispatch of the UoW energy system.

3.2 Multi-energy system modelling and optimisation

- **Formulation of optimisation considering thermal storages**

The UoW multi-energy system was modelled using the energy hub concept. An optimisation problem was formulated to minimize the energy costs of the operation of the UoW energy system. The following assumptions were made to build the optimisation model:

- Aggregations of the CHP generators as one CHP generator.
- Aggregation of the gas boilers as one gas boiler.

- Aggregation of the thermal storage units as one thermal storage unit.
- The start/end thermal storage level at midnight is set at 50%.
- Maximum allowable heat dump was set to xx MWh

The optimisation problem was formulated following the well-established scheduling problem in power systems [1] extended to a multi-energy system. The optimisation model considers limits to energy conversion and energy storage within the local energy system as constraints for the optimisation problem.

$$\boldsymbol{Minimize} \sum_{\alpha,\beta,\ldots\zeta} \mathrm{E}_{\alpha} \boldsymbol{P}_{\alpha}$$

where, $\mathbf{E}_{\alpha}$ is the cost of energy-vector $\boldsymbol{\alpha}$ at Energy hub input, $\boldsymbol{P}_{\alpha}$ is the power exchanged of energy-vector $\boldsymbol{\alpha}$ with the external energy supply.

The equality constraints were the set of equations representing the energy balance equations. These are shown in matrix form illustrating the conversion of energy from the hub input $\boldsymbol{P^{in}}$ to the demands $\boldsymbol{P^{out}}$ described with a coupling matrix C in Equation 2 as,

$$\underbrace{\begin{bmatrix} \boldsymbol{P}_{out}^{\alpha} \\ \boldsymbol{P}_{out}^{\beta} \\ \vdots \\ \boldsymbol{P}_{out}^{\zeta} \end{bmatrix}}_{\boldsymbol{P}_{out}} = \underbrace{\begin{bmatrix} c_{\alpha\alpha} & c_{\beta\alpha} & \cdots & c_{\zeta\alpha} \\ c_{\alpha\beta} & c_{\beta\beta} & \cdots & c_{\zeta\beta} \\ \vdots & \vdots & \ddots & \vdots \\ c_{\alpha\zeta} & c_{\beta\zeta} & \ldots & c_{\zeta\zeta} \end{bmatrix}}_{\mathrm{C}} \underbrace{\begin{bmatrix} \boldsymbol{P}_{in}^{\alpha} \\ \boldsymbol{P}_{in}^{\beta} \\ \vdots \\ \boldsymbol{P}_{in}^{\zeta} \end{bmatrix}}_{\boldsymbol{P}_{in}}$$

Where $\boldsymbol{\alpha}, \boldsymbol{\beta}, \ldots, \boldsymbol{\tau}$ are a set of energy vectors. The coupling matrix C depend on the converter efficiencies, the hub internal connection topology and the quantity of power conversion. The coupling matrix is derived by expressing an independent energy balance equation for each energy vector. The derivation of the coupling matrix of an energy hub is introduced in. The inequality constraints are based on the technical constraints of equipment: rated power output capacity, minimum power output and maximum and minimum levels to be maintained in an energy storage.

The optimisation was a non-linear programming problem and was solved using the MATLAB software and the MATLAB function ‘fmincon’ was used for the optimisation [2].

- **Quantification of predicted savings through optimal operation**

Figure 7 shows a monthly breakdown of the energy costs between the digital twin with existing controls and the optimisation results. Compared to the Digital Twin with existing controls, the optimisation results show lower electricity import costs and gas boiler gas costs, but higher CHP generator gas costs. These differences in the electricity import and gas costs are larger during the summer months. Overall, the monthly operational costs of the optimisation are lower than the Digital Twin with the existing controls.

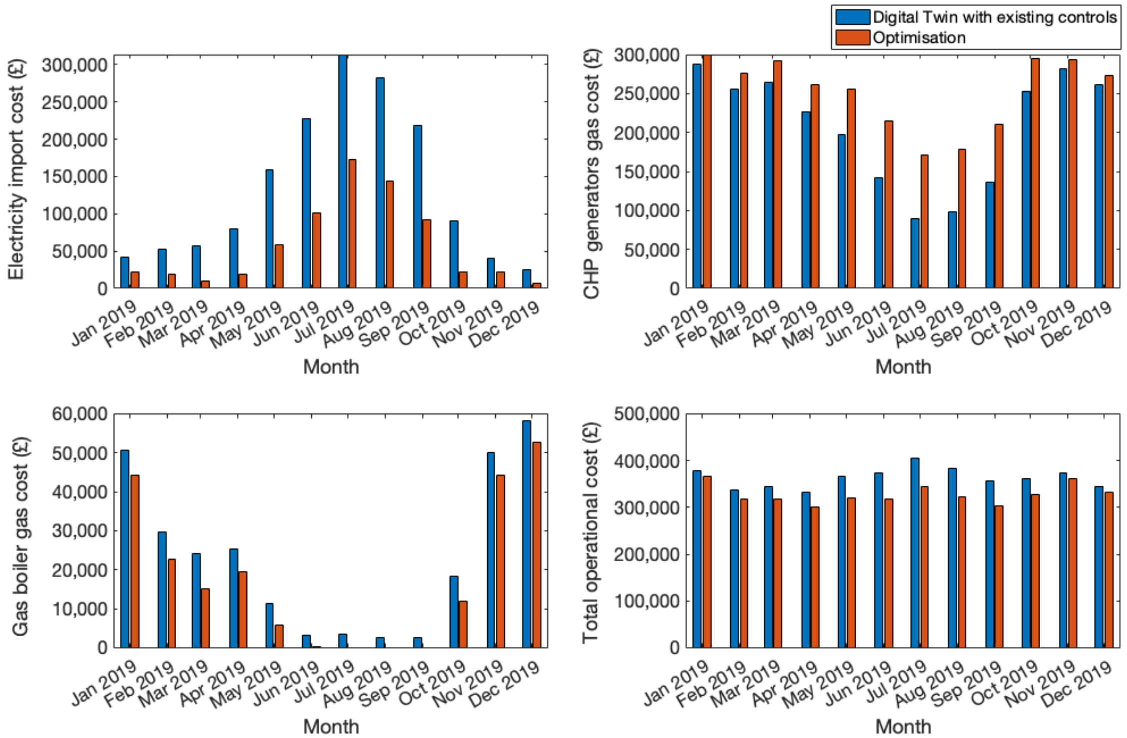

Figure 7. Monthly breakdown of energy costs; comparison of Digital Twin with existing controls with optimisation results.

There are two main areas of potential energy cost savings identified:

- Reducing electricity import (the optimisation model shows a 56.52% reduction in electricity imports compared to the Digital Twin with existing controls);
- Reducing the gas boiler use in favour of the CHP generators (22.61% reduction in natural gas consumption in gas boilers compared to the Digital Twin with existing controls);

However, to achieve the above two potential cost savings 21.21% increase in the gas consumption of the CHP generators is required.

Figure 8 shows the breakdown of monthly cost savings suggested by the optimisation compared to the Digital Twin with existing control rules. Over the year, a 9.91% energy bill saving opportunity was identified compared to the Digital Twin with existing controls (Approximately £432,290 per year) from the operation from the optimisation. Higher cost savings are suggested in summer months compared to the winter months.

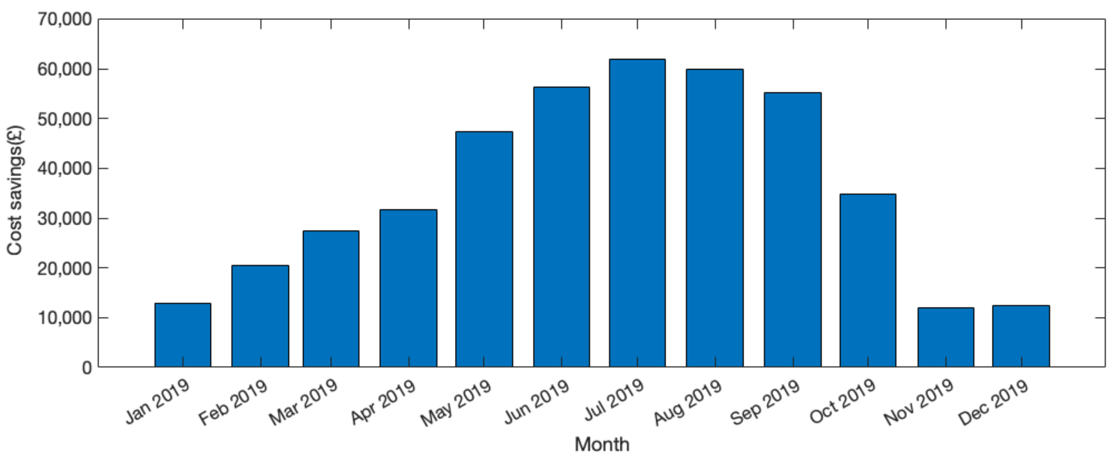

Figure 8. Cost savings suggested by optimisation compared to the Digital Twin with existing controls.

- **Operation of the thermal storage units suggested by the optimisation**

Figure 9 shows the hourly thermal storage level variation for days in the three seasons obtained from the optimisation results. Red dotted lines show the average profile of the optimisation data.

The operation of thermal storage units in the optimisation shows clear differences compared to the Digital Twin using existing controls (Figure 6). The thermal storage units in the optimisation show constant state of charge throughout the day in winter compared to the Digital Twin with existing controls where a charging peak was happening between 2am and 6am. In summer, the thermal storage units show constant state of charge in the Digital Twin with existing controls (Figure 6). But the optimisation shows two dips in the thermal storage levels: at 6-7am and at 3pm.

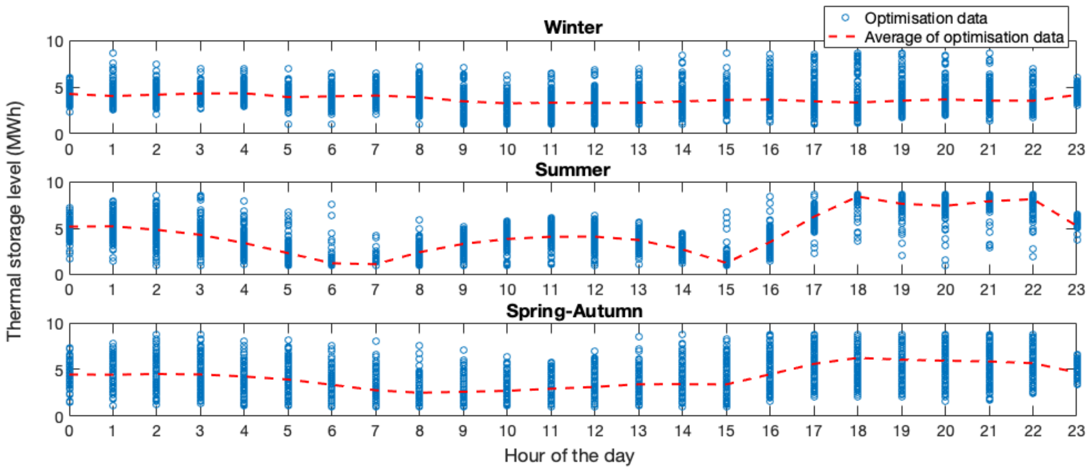

Figure 9. Seasonal variation of thermal storage levels suggested by the optimisation.

3.3 New lookup tables for the thermal energy storage units using the optimisation results

The following sequence of steps were used to derive new lookup tables for the thermal energy storage units using the optimisation results:

1. **Generate a large dataset of thermal storage levels for optimal operation of UoW energy system.**

An optimisation study was conducted for one full year, for 24-hour intervals in half-hour granularity as shown in the Section 3.2. Then half-hourly thermal energy storage levels were obtained as an output from the optimisation together with other input parameters of the optimisation; outside ambient temperature (OAT), heat demand, electricity demand and electricity import price.

2. **Identify the charging and discharging patterns and correlating factors to the thermal storage levels.**

The optimisation results of the thermal storage levels were analysed to recognise patterns and relation to parameters such as OAT, hour of the day (HoD), month and season.

3. **Train, test and validate regression tree models to predict the thermal storage levels.**

The Regression Learner App in the MATLAB statistics and machine learning toolbox was used to train regression tree models with different predictor parameters (i.e., variables that might have an impact on the thermal storage charge discharge patterns) to predict the SoC of UoW thermal storage units using the optimisation results of one full year (year 2019).

A five-fold cross validation procedure (partition the dataset into folds and estimate accuracy on each fold) available in the Regression Learner App in MATLAB was used to protect against overfitting and to examine the predictive accuracy of the fitted model. This method calculates the average test error over all folds and gives a good estimate of the predictive accuracy of the final model trained with all the data.

Figure 10 shows estimates of predictor importance for the regression tree by summing changes in the risk due to splits on every predictor and dividing the sum by the number of branch nodes.

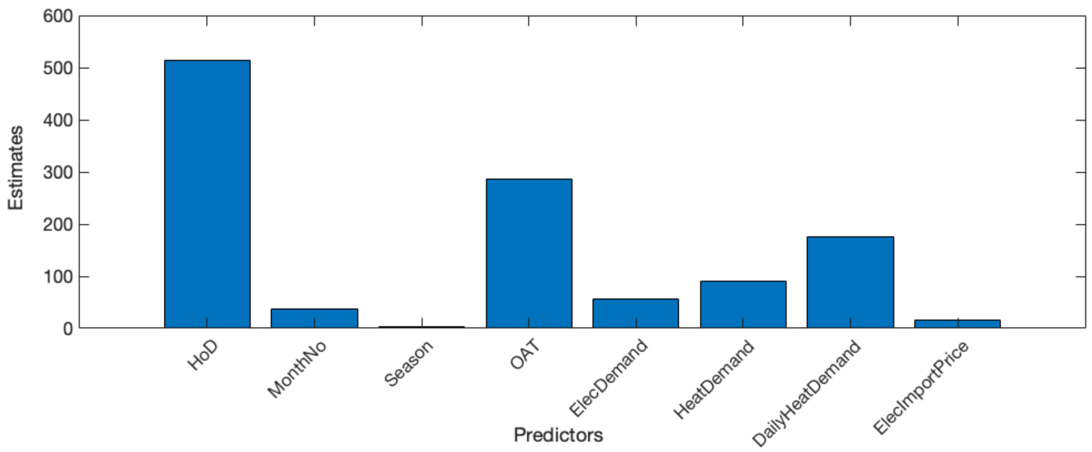

Figure 10. Predictor importance of the trained regression tree model to predict SoC of UoW thermal storage units.

The trained 'Fine' regression tree model with all the predictor parameters in Figure 10 had Mean absolute error (MAE) of 650.94 (equivalent to 15.6% of the mean of measured thermal storage values) when doing the cross validation.

Hour of the day (HoD) and outside ambient temperature (OAT) were identified as being the most important variables in predicting the thermal storage units state of charge among the 6 variables studied. This is shown by their high estimates compared to other variables.

Even though the daily heat demand, has high importance, these predictors cannot be used easily to improve the existing controls. Accurate forecast models of these parameters would be needed.

- Using optimisation outputs for SoC of thermal storage units two more regression tree models were trained, one using the HoD for separate seasons (as an update of the existing one) and the second one using the HoD and the average OAT during the 4-hour period.
- MAE of these two regression tree models were calculated in the cross-validation procedure. The Season regression tree model has a MAE (winter MAE=747.01, Summer MAE=668.49, Spring/Autumn MAE=1189.2) of 868.23 (equals to the average MAE of the three seasons) and the OAT regression tree model has a MAE of: 798.36. As expected by the higher importance to predict thermal storage units level of OAT compared to season, the MAE is lower for the OAT regression tree model than for the Season regression tree model.

4. **Derive new lookup tables using the trained regression-decision tree models to predict the thermal storage levels**.

The OAT and Season regression tree models were used to derive two lookup tables. Aggregated thermal storage targets obtained from the regression tree models were dis-aggregated to produce separate storage targets for the two energy centres in 2:1 ratio.

For the OAT lookup table, the thermal storage units targets for each four-hour periods were predicted for temperature from -5˚C to +30˚C with interval of 1˚C.

Table 5. Lookup table for target thermal energy storage levels based on Seasons.

Time	Target storage level (MWh)

	Winter		Spring/Autumn		Summer	
	MBH	CEC	MBH	CEC	MBH	CEC
6am	2.68	1.34	2.22	1.11	0.81	0.4
10am	2.18	1.09	1.79	0.89	2.56	1.28
2pm	2.32	1.16	2.26	1.13	1.81	0.9
6pm	2.24	1.12	4.15	2.08	5.63	2.81
10pm	2.37	1.18	3.77	1.88	5.43	2.72
2am	2.81	1.4	2.99	1.5	3.22	1.61

Table 6. Lookup table for target thermal energy storage levels based on OAT.

OAT (Degrees Celsius)	Target storage level (MWh)											
	Time											
	MBH						CEC					
	6am	10am	2pm	6pm	10pm	2am	6am	10am	2pm	6pm	10pm	2am
-5	2.64	2.22	2.14	1.54	2.17	2.41	1.32	1.11	1.07	0.77	1.09	1.2
-4	2.64	2.22	2.14	1.54	2.17	2.41	1.32	1.11	1.07	0.77	1.09	1.2
-3	2.64	2.22	2.14	1.54	2.17	2.57	1.32	1.11	1.07	0.77	1.09	1.29
-2	2.69	2.22	2.14	1.54	2.17	2.73	1.34	1.11	1.07	0.77	1.09	1.37
-1	2.82	2.22	2.14	1.54	1.87	2.66	1.41	1.11	1.07	0.77	0.93	1.33
0	2.78	2.22	2.14	1.54	2.07	2.77	1.39	1.11	1.07	0.77	1.04	1.39
1	2.67	2.31	2.14	1.64	2.14	2.85	1.33	1.16	1.07	0.82	1.07	1.43
2	2.44	2.25	2.37	1.78	2.24	2.98	1.22	1.13	1.18	0.89	1.12	1.49
3	2.66	2.27	2.39	1.57	2.14	2.71	1.33	1.13	1.2	0.79	1.07	1.35
4	2.88	2.51	2.14	1.76	2.24	2.89	1.44	1.26	1.07	0.88	1.12	1.45
5	2.61	2.4	2.38	2.16	2.63	2.93	1.3	1.2	1.19	1.08	1.31	1.46
6	2.55	2.31	2.35	1.88	2.58	2.9	1.28	1.15	1.18	0.94	1.29	1.45
7	2.68	2.11	2.35	2.02	2.84	2.95	1.34	1.06	1.17	1.01	1.42	1.47
8	2.44	2.12	2.27	3.04	3.31	3.19	1.22	1.06	1.13	1.52	1.65	1.59
9	2.38	1.9	2.58	2.88	3.31	3.29	1.19	0.95	1.29	1.44	1.66	1.64
10	2.07	1.52	2.5	3.95	3.79	3.12	1.04	0.76	1.25	1.97	1.9	1.56
11	1.82	1.28	2.57	4.71	4.25	2.77	0.91	0.64	1.28	2.35	2.13	1.39
12	1.12	1.43	2.38	4.51	5.25	2.81	0.56	0.72	1.19	2.25	2.63	1.4
13	1.02	1.55	2.53	5.04	5.37	2.86	0.51	0.77	1.27	2.52	2.69	1.43
14	0.77	1.93	2.55	5.36	5.18	3.19	0.38	0.97	1.27	2.68	2.59	1.59
15	0.76	1.89	1.7	5.33	5.5	3.33	0.38	0.95	0.85	2.67	2.75	1.67
16	0.68	2.35	1.73	5.56	5.53	3.11	0.34	1.18	0.87	2.78	2.76	1.56
17	0.68	2.18	1.94	5.72	5.65	3.63	0.34	1.09	0.97	2.86	2.83	1.82
18	0.67	2.48	1.79	5.74	5.63	3.02	0.33	1.24	0.9	2.87	2.81	1.51
19	0.67	2.52	1.74	5.74	5.48	3.02	0.33	1.26	0.87	2.87	2.74	1.51
20	0.67	2.57	1.72	5.75	5.41	3.02	0.33	1.29	0.86	2.87	2.71	1.51
21	0.67	2.78	1.67	5.81	5.56	3.02	0.33	1.39	0.83	2.9	2.78	1.51
22	0.67	2.6	1.75	5.81	5.56	3.02	0.33	1.3	0.88	2.9	2.78	1.51
23	0.67	2.54	1.91	5.81	5.56	3.02	0.33	1.27	0.95	2.9	2.78	1.51
24	0.67	2.83	1.67	5.81	5.56	3.02	0.33	1.41	0.83	2.9	2.78	1.51
25	0.67	2.83	1.67	5.81	5.56	3.02	0.33	1.41	0.83	2.9	2.78	1.51
26	0.67	3.21	1.77	5.81	5.56	3.02	0.33	1.61	0.88	2.9	2.78	1.51
27	0.67	3.27	1.77	5.81	5.56	3.02	0.33	1.64	0.88	2.9	2.78	1.51
28	0.67	3.27	1.77	5.81	5.56	3.02	0.33	1.64	0.88	2.9	2.78	1.51
29	0.67	3.27	2.03	5.81	5.56	3.02	0.33	1.64	1.02	2.9	2.78	1.51
30	0.67	3.01	2.03	5.81	5.56	3.02	0.33	1.51	1.02	2.9	2.78	1.51

4 Results

Two new lookup tables were derived from the optimisation results:

1. a lookup table based on seasons (Table 5) similar to the existing one (Table 4) except that the values were updated; and,

a lookup table based on outside air temperature (

2. Table 6).

The impacts on these lookup tables on the operation of the UoW energy system will be compared using:

1. A Digital Twin using the existing lookup table (the same digital twin shown in Sections 3.1 and 3.2);
2. A Digital Twin using the updated lookup table based on Seasons; and,
3. A Digital Twin using the updated lookup table based on OAT.

4.1 Impacts on daily operation

Figure 11 and Figure *12* show the operation for the thermal storage units of the Digital Twin using the three lookup tables for a winter day and a summer day compared with the thermal store state of charge of the optimisation. Target storage levels of the three lookup tables are also compared with the thermal store state of charge levels of the optimisation. The thermal storage units level and target thermal storage values of the OAT and Season lookup tables are closer to the optimisation than the operation with existing lookup table. A better accuracy may be achieved by creating lookup tables with more than two predictors. For instance, a lookup table based on hour of the day, OAT and current heat demand.

The thermal storage units of the Digital Twin with the new lookup tables show a more constant state of charge throughout the day in winter compared to the operation with the existing lookup table where a charging peak was happening between 2am and 6am.

For the summer day, the thermal storage units have a constant state of charge with the existing lookup table. In contrary, the operation with the new lookup tables shows a dip in the morning from 2am to 6am and a peak in the evening from 2pm to 10pm.
For the morning dip: this follows the findings from the optimisation model shown in section 3.2 (Figure 9).
For the evening peak: this follows the findings from the optimisation model shown in section 3.2 (Figure 9) which recommended charging the thermal storage units using the CHP generators during time of high electricity import prices to limit the import.

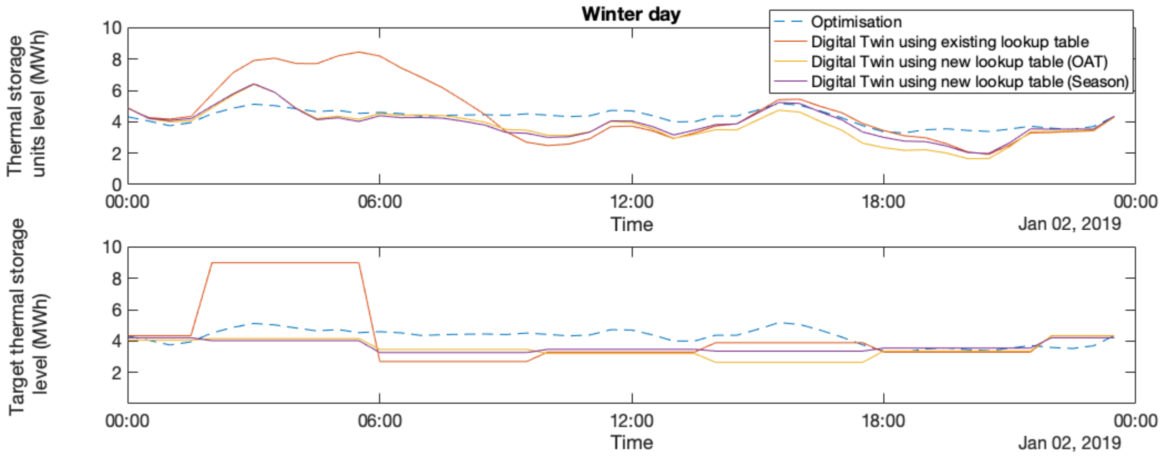

Figure 11. Variation of the thermal storage units level (MWh) based on the three lookup tables and the optimisation results on a winter day.

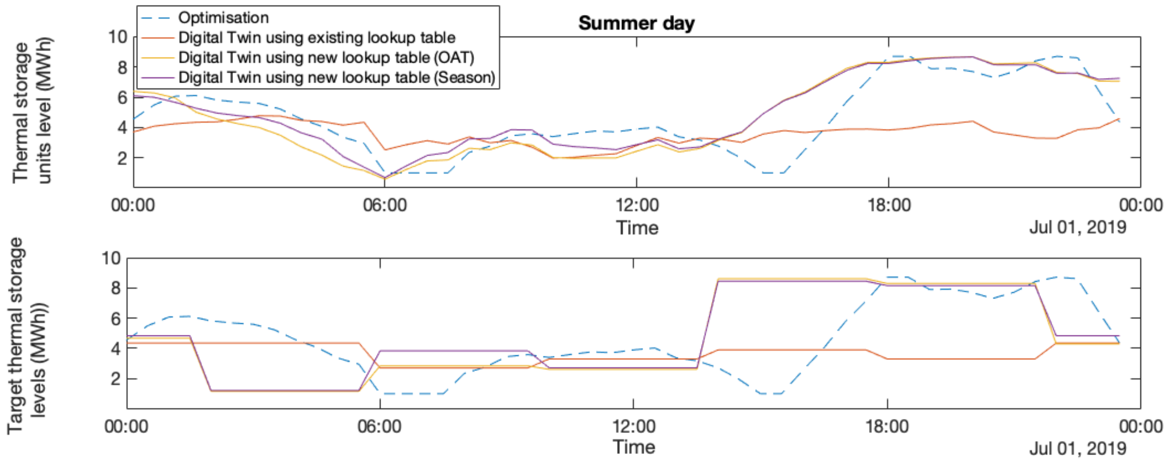

Figure 12. Variation of the thermal storage units levels (MWh) based on the three lookup tables and the optimisation results on a summer day.

These changes in the control of thermal storage units impacts the amount of electricity imported, the operation of the CHP generators and the gas boilers. Figure 13 and Figure 14 show the profiles of the electricity import, the CHP generators electricity and heat output of the same winter and summer day as above. In the winter day, the Digital Twin with the 3 lookup tables have similar patterns for the electricity imported and the CHP generators electricity outputs. The gas boilers heat output in the Digital twins with OAT and Seasons lookup tables are less than that of the Digital Twin with existing lookup table between 2am-6am and then swap after 6am until 10am. In comparison to the optimisation results, the digital twins with the three lookup tables import more electricity. This is due to the constraints implemented for the running of the CHP generators in the digital twin (e.g., minimum running load and minimum starting load) which have not been considered in the optimisation model.

In the summer day, the import electricity and gas boiler thermal energy output of the Digital Twin with the new OAT and Season lookup tables are less than the Digital Twin with the existing lookup table. The CHP generator electricity output of the Digital Twin with the two new lookup tables are greater than that of the Digital twin with existing lookup table during most time of the day. Overall, there is less export of electricity in the digital twins using the new lookup tables compared to the digital twin using the existing one. In the digital twins, the CHP generators electricity output is constrained by the amount of heat of the site whereas dumping heat to increase the electricity generation is possible in the optimisation model.

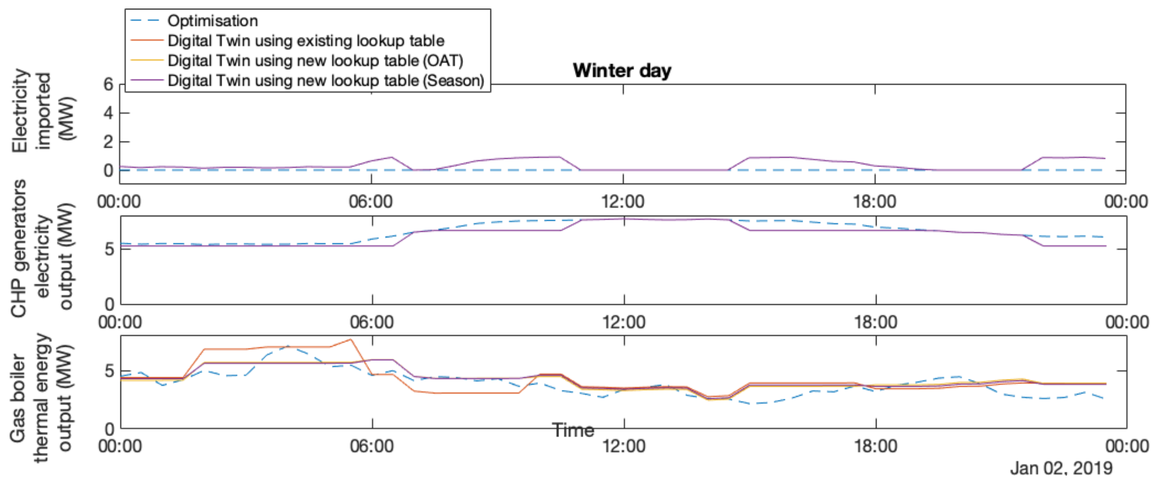

Figure 13: Half-hourly electricity import, CHP generators electricity output and gas boilers heat output on a winter day (note: Electricity imported, and CHP generators electricity outputs are the same for the 3 digital twins)

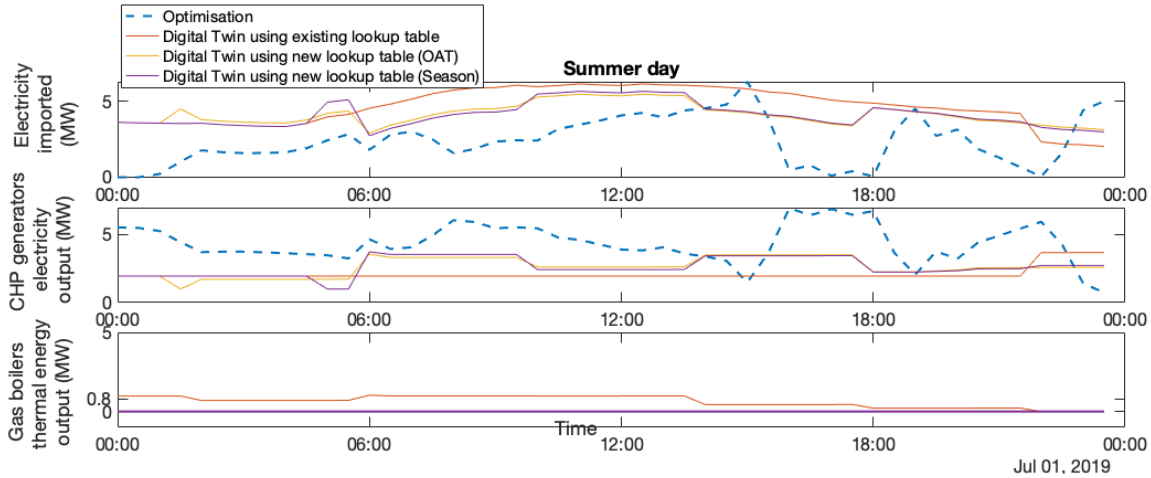

Figure 14: Half-hourly electricity import, CHP generators electricity output and gas boilers heat output on a summer day (note: Gas boilers thermal energy output of the two Digital twins with new lookup tables and of optimisation are equal to zero)

Figure 15 shows the difference in the monthly electricity imports, the gas consumptions from the gas boilers and the CHP generators, and the amount of heat dumped between the operation of Digital Twin with the three lookup tables and the optimisation. There are no significant differences between the digital twins with the three lookup tables themselves. The major difference is when the digital twins are compared with the optimisation results and the amount of heat dumped. In the optimisation model, large amount of heat is dumped during summertime to allow the CHP generators to run regardless of the heat demand of the site to limit the import of electricity.

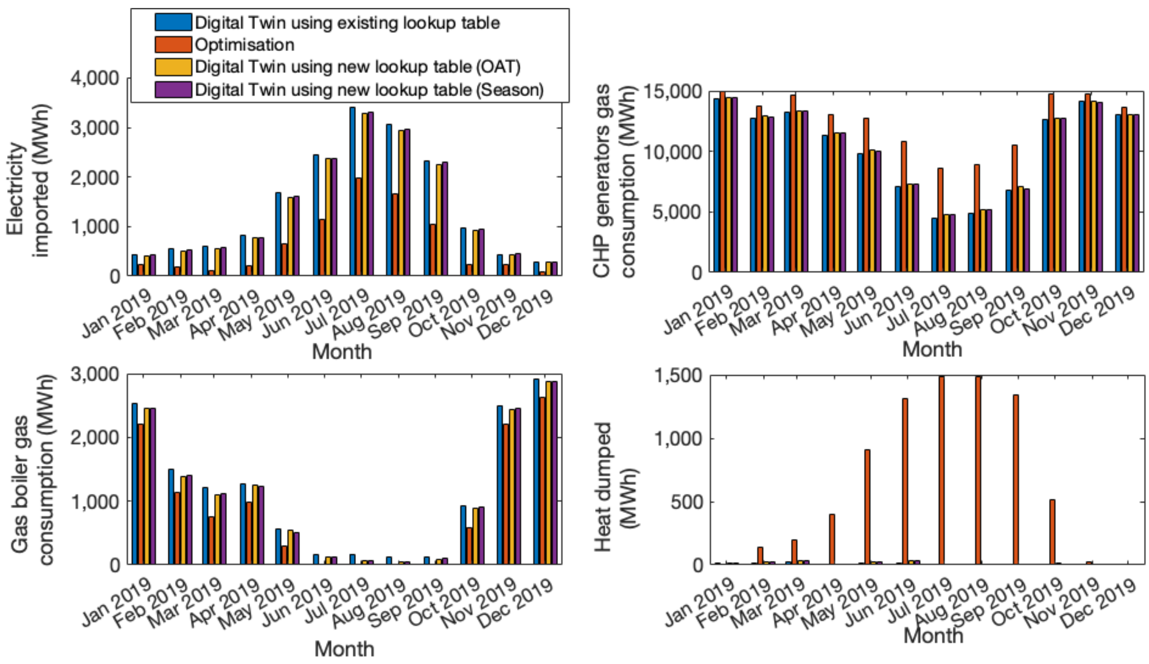

Figure 15: Monthly breakdown of the electricity imported, gas consumption from the CHP generators and the gas boilers and the heat dumped for the digital twins with the three lookup tables and the optimisation results

Table 7 compares the annual electricity imports, the use of the gas boilers, CHP generators, and the amount of heat dumped of the optimisation and the operation Digital Twin with two new lookup tables, against the operation of Digital Twin with existing lookup table for the year 2019.

Table 7. Comparison between the operation of Digital Twin with existing lookup table, optimisation results and Digital Twin with new lookup tables (the percentage values within the bracket shows % change compared to the Digital Twin using existing rules).

Parameter	Digital Twin using existing lookup table	Optimisation	Digital Twin using new lookup table (OAT)	Digital Twin using new lookup table (Season)
Electricity imported (MWh)	16,962 (0%)	7,754 (-54.3%)	16,375 (-3.5%)	16,539 (-2.5%)
CHP generators gas consumption (MWh)	124,771 (0%)	151,079 (+21.1%)	126,449 (+1.3%)	125,979 (+1.0%)
Gas boilers gas consumption (MWh)	14,140 (0%)	10,828 (-23.4%)	13,414 (-5.1%)	13,475 (-4.7%)
Heat dumped (MWh)	250 (0%)	7,812 (+3025%)	267 (+6.8%)	138 (-44.8%)

4.2 Monthly operational cost breakdown

The operational costs were calculated using a fixed gas price of 2 p/kWh and a peak/off-peak electricity import price (see Figure A. 1)

Figure 16 shows the monthly breakdown of the operational costs for the Digital Twin using the three lookup tables as well as from the existing operation (historical data) and the optimisation model.

- Overall, there are no significant changes between the three Digital Twins Over the year, the Digital Twin using the new lookup table (OAT) has an operational cost £49,000 (-1.1%) lower than the Digital Twin using the existing lookup table. The Digital Twin using the new lookup table (OAT) has an operational cost £65,000 (-1.5%) lower than the Digital Twin using the existing lookup table.
- Largest gap between the Digital Twin using the three lookup tables and the optimisation model happens during summertime. This is explained by the possibility to dump heat in the optimisation model to increase the operation of the CHP generators and not in the Digital Twin.

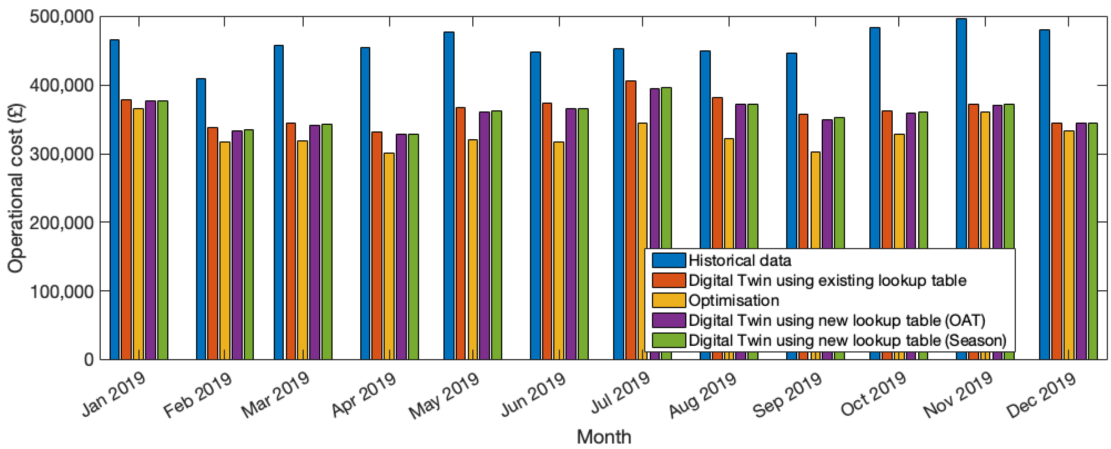

Figure 16: Monthly breakdown of the operational costs of the UoW energy system.

4.3 Greenhouse gases emissions

To calculate the greenhouse gases emissions (GHG), the factor of 0.23314 $kgCO_2e/kWh_{electricity}$ was used for the electricity import and 0.20449 $kgCO_2e/kWh$ for gas (ref UK Government GHG Conversion Factors for Company Reporting 2020).

Figure 17 shows the total GHG emissions for a year from the historical data, the Digital Twin using the three lookup tables and the optimisation model. The GHG emissions are similar for the Digital Twin using the three lookup tables regardless of the version of the lookup table used for the thermal storage units. The optimisation model shows an 8% increase in GHG emissions compared to the Digital Twin using the three lookup tables. This is explained by the decrease in electricity import in favoured of electricity produced by the CHP generators. As the electricity produced by the CHP generators have a higher carbon intensity than the grid electricity, this leads to an increase of the total GHG emissions.

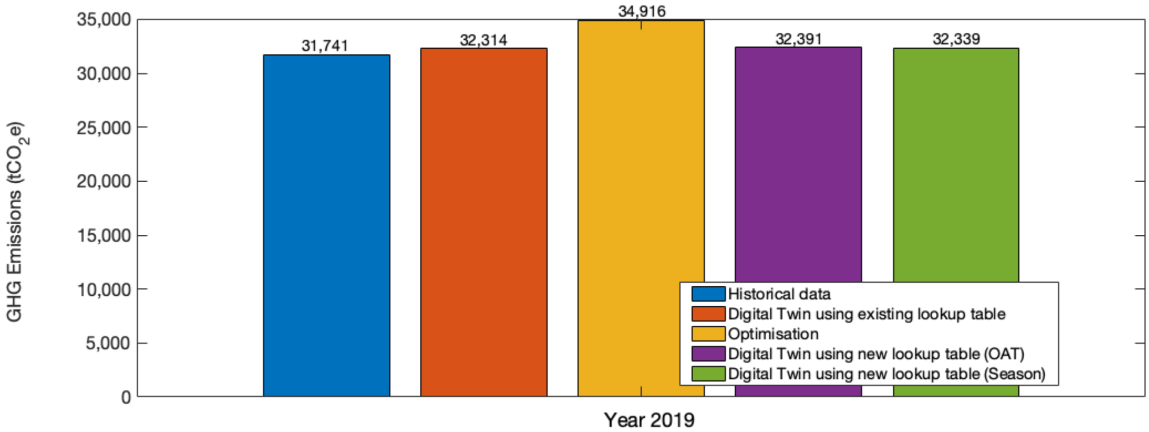

Figure 17: GHG emissions for the year 2019 for energy system of the UoW.

5 Conclusions and Further Work

The improvements of the lookup tables for the thermal storage units can lead to cost savings for the UoW. This would not require further changes to the system. The optimisation model showed that further decrease of the operational costs of the system can be achieved by increasing the amount of heat dumped to increase the running time of the CHP generators. However, this would lead to an increase of the GHG emissions and goes against the objective of the UoW.

The same approach described in this article can be applied to other part of the system (e.g. replacement of the lookup table to predict heat demand for every four-hour periods). The development of probability forecasts for the heat demand and the state of charge of the thermal storages would also help to improve the operation of UoW energy system.

Additional constraints need to be included in the optimisation model to provide a more realistic behaviours of the control of the CHP generators (E.g., dumping of heat). Methods to automatically update the lookup tables would help to improve the operation with the evolvement of UoW energy system with increasing demands and onsite generation technologies. The optimisation results can also be used to derive improved the control rules of CHP operation and the gas boilers.

References

[1] Wood, A. J., Wollenberg, B. F., & Sheblé, G. B. (2013). *Power generation, operation, and control*. John Wiley & Sons.

[2] https://uk.mathworks.com/help/optim/ug/fmincon.html

Appendix

Table A. 1. The predicted thermal energy load lookup table.

4 Hour Average Ambient Temperature	LTHW System Load (MWh) For Stated Period					
	2am-6am	6am-10am	10am-2pm	2pm-6pm	6pm-10pm	10pm-2am
-1	18.4	33.0	29.2	32.0	31.5	27.0
0	20.4	33.0	32.1	32.0	31.5	33.3
1	21.9	27.2	32.1	31.5	27.9	17.7
2	22.3	29.9	22.3	33.0	27.5	20.0
3	18.2	15.8	22.3	25.4	24.8	17.4
4	13.6	21.0	15.3	29.9	21.9	13.8
5	13.8	19.0	27.0	17.6	14.4	16.0
6	15.7	20.1	14.3	14.3	20.7	13.6
7	12.0	13.4	20.3	26.2	17.0	12.9
8	12.4	20.7	17.8	13.3	13.3	12.8
9	17.1	15.3	19.4	20.3	27.0	13.8
10	11.2	13.5	17.0	21.0	15.3	16.2
11	7.2	10.9	11.9	12.9	14.0	8.6
12	5.3	8.0	12.0	10.7	9.7	7.6
13	6.9	7.6	9.2	11.3	11.9	8.1
14	3.8	5.9	8.0	12.0	10.3	6.7
15	4.4	5.5	8.6	11.1	7.9	6.1
16	4.5	6.3	5.0	9.0	8.4	6.0
17	3.8	4.9	5.2	6.0	5.8	5.1
18	3.6	5.1	4.2	3.7	5.2	4.9
19	3.0	6.4	4.3	4.6	5.7	4.4
20	4.1	8.9	4.1	4.0	4.0	6.1
21	4.6	8.0	4.0	3.8	3.0	6.1
22	4.4	7.7	4.2	4.0	3.3	6.1
23	7.5	9.8	6.0	3.7	3.2	6.1
24	7.6	9.8	9.6	3.3	3.2	6.1
25	6.9	9.0	7.5	3.6	3.9	6.1
26	6.5	8.5	7.0	3.6	4.5	6.7

Predictive Learning Cmd: ON

O.A.T 10.0 °C

Energy in Tanks: 4.6

1 CHP @ 100% = 3.2 MWh
2 CHP's @ 100% = 6.4 MWh
3 CHP's @ 100% = 9.6 MWh

CHP 1 CHP 2 CHP 3
105.0 105.0 66.6

Energy required to produce for the remaining time period = 7.605

Energy in Tank + the Energy from the CHP's = the Energy from the system. If there is a short fall between the Energy Required (this table) and the Energy in the system, then the Boilers will be called into action to top up.

Table A. 2. Heat energy output from energy supply and conversion units for 4hr operation.

Name	kW Rating	MWh/4 Hour Period
CEC CHP1	2,000	8.0
CEC CHP2	2,000	8.0
MBH CHP1	1,600	6.4
MBH CHP2	1,600	6.4
MBH CHP3	1,600	6.4
MBH Boiler 1	4,870	19.48
CEC Boiler 1	5,240	20.96
MBH Boiler 2	4,870	19.48

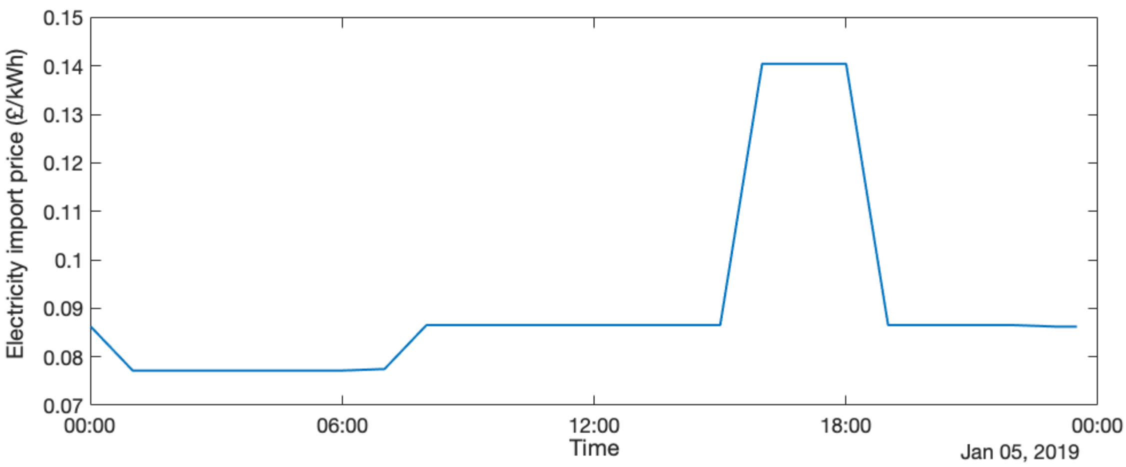

Figure A. 1. Peak/off-peak electricity import prices.