

Pre-Feasibility Modelling and Market Potential Analysis of a Cloud-Based CHP Optimiser

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ABSTRACT

Smart control system technologies for combined heat and power (CHP) units are not previously reported in literature, and have potential to generate significant savings. Only minimal capital investment is required in infrastructure and software development. A live cloud-based solution has therefore been developed, and installed in a real UK supermarket store, to optimise CHP output based upon predicted price forecasts, and live electricity and heat demand data. This has allowed validation of the optimiser price forecasts, and predicted cost savings, and a model of the optimiser has therefore been applied to three case study sites. The model itself has also been validated against the installed optimiser data. The pre-feasibility analysis undertaken indicates cost savings between 2% and 12%. CHP units sized within the feasible operating range, above a part load level of 0.65, generate the greatest percentage savings. This is because the optimiser has the greatest flexibility to control the CHP output. However, larger units, even though less nearly optimal, may actually generate greater overall savings and would therefore be targeted for earlier optimiser implementation. Installation costs are not expected to vary greatly from site-to-site. Some stores, though, show no material improvement over the existing control systems, demonstrating the value of the pre-feasibility analysis using the model. Though waste heat increases significantly with all strategies, the propensity to sell this heat within the UK is likely to improve in the near future.

INTRODUCTION

Combined heat and power (CHP) units are increasingly popular as reliable on-site distributed energy systems, able to supply power more efficiently than by conventional means (Acha, 2013; Acha *et al.*, 2018). However, CHPs are capital intensive, meaning a robust business case must be developed to mitigate risk for investors (Beith, 2011). The optimal CHP operating point for savings generation depends on a variety of site-specific factors, meaning a smart control system has potential to improve investment returns. Some control systems already allow ‘load-following’, matching output to the store’s electricity demand, though variation in electricity import and export prices are not fully exploited. This research presents a cloud-based optimiser to address this challenge, constituting applied academic research, not from industry, which we believe is completely novel. Although substantial research has been conducted into sizing and operating CHP systems, real-time control for their optimal operation has not been widely used in buildings (Yu *et al.*, 2017; Mascuch *et al.*, 2018). Some research has been conducted into the long term impact of electricity prices on CHP profitability, but nothing on live output optimisation (Sundberg and Henning, 2002). Grid unpredictability is also increasing faster than ever, causing electricity price fluctuations, and increasing the utility of the flexible optimiser developed (National Grid, 2018). The optimiser developed and described here has been installed on a real CHP system in a UK supermarket to test its practical utility. The trial conducted is detailed in the ‘Trial Outline’ section, with the results and learnings analysed in the ‘Trial Results’ section. A model of the optimiser has also been developed, using store data to simulate performance. The ‘Simulation Results’ section presents the model results applied to three case study stores. The final ‘Discussion’ section explores the benefits and limitations of the optimiser and the site-specific factors determining feasibility for implementation.

METHODOLOGY

The CHP optimiser aims to select the optimal output level for the unit via continuous monitoring, implemented through a two-level cloud-based control system. The only inputs required are price forecasts and heat and electricity demand. The objective function of the optimisation problem, shown in equation 1, involves the operational savings relative

to business as usual (BaU) operation. The optimisation problem is solved by the cloud-based controller, which then communicates the set point part load output to the on-site controller. The latter then maintains the CHP unit at this set point and the process is repeated whenever it publishes new data back to the cloud-based controller.

$$S_{\text{tot}} = (C_{\text{noCHP}} - C_{\text{tot}}) / C_{\text{noCHP}} \quad (1)$$

where C_{tot} is the operational cost using the CHP unit and C_{noCHP} is the operational cost without the CHP unit. The operational cost with no CHP unit is given in equation 2. P_{fuel} and P_{imp} are the natural gas and electricity import prices respectively, and η_{boil} is the boiler efficiency. D_{el} and D_{th} are the total electricity and heat demand of the store respectively, also expressed explicitly in the electricity and heat balances, shown in equations 3 and 4 respectively. $P_{\text{CHP_el}}$ and $P_{\text{CHP_th}}$ are the electricity output and thermal output of the CHP engine respectively, $P_{\text{grid_imp}}$ and $P_{\text{grid_exp}}$ are the amount of electricity imported and exported from the grid respectively, and P_{boil} and P_{wast} are the heat from the boiler and the excess waste heat respectively.

$$C_{\text{noCHP}} = (D_{\text{th}} \cdot P_{\text{fuel}} / \eta_{\text{boil}}) + (D_{\text{el}} \cdot P_{\text{imp}}) \quad (2)$$

$$D_{\text{el}} = P_{\text{CHP_el}} + P_{\text{grid_imp}} - P_{\text{grid_exp}} \quad (3)$$

$$D_{\text{th}} = P_{\text{CHP_th}} + P_{\text{boil}} - P_{\text{wast}} \quad (4)$$

The operational cost with the CHP unit is given by equation 5. C_{CHP} , C_{boil} , C_{imp} and R_{exp} , are the CHP cost, boiler cost, electricity import cost and electricity export revenue respectively, as defined in equations 6–9. Variables are consistent with those previously defined. F_{CHP} is the fuel input required to the CHP, P_{exp} is the electricity export price and P_{boil} , $P_{\text{grid_imp}}$ and $P_{\text{grid_exp}}$ are the power produced by the boiler, imported from the grid and exported to the grid respectively.

$$C_{\text{tot}} = C_{\text{CHP}} + C_{\text{boil}} + (C_{\text{imp}} - R_{\text{exp}}) \quad (5)$$

$$C_{\text{CHP}} = P_{\text{fuel}} \cdot F_{\text{CHP}} \quad (6)$$

$$C_{\text{boil}} = P_{\text{boil}} \cdot P_{\text{fuel}} \cdot (1 / \eta_{\text{boil}}) \quad (7)$$

$$C_{\text{imp}} = P_{\text{grid_imp}} \cdot P_{\text{imp}} \quad (8)$$

$$R_{\text{exp}} = P_{\text{grid_exp}} \cdot P_{\text{exp}} \quad (9)$$

The CHP engine can only operate above a specified minimum level, pl_{min} . This is incorporated in the optimization problem using a binary variable y_{CHP} , where $y_{\text{CHP}} \in [0,1]$; 1 corresponds to the CHP unit being on and 0 to the unit being off. In addition, an arbitrary large number M is required to retain the linearity of the model. When the CHP unit is off, pl_{CHP} is 0, while when it is on, pl_{CHP} can vary between pl_{min} and 1:

$$pl_{\text{CHP}} \geq pl_{\text{min}} - M \cdot (1 - y_{\text{CHP}}) \quad (10)$$

$$pl_{\text{CHP}} \leq 1 + M \cdot (1 - y_{\text{CHP}}) \quad (11)$$

$$pl_{\text{CHP}} \geq 0 - M \cdot y_{\text{CHP}} \quad (12)$$

$$pl_{\text{CHP}} \leq 0 + M \cdot y_{\text{CHP}} \quad (13)$$

The heat output of the boiler P_{boil} and the heat wasted P_{wast} are always positive:

$$P_{\text{boil}} \geq 0 \quad (14)$$

$$P_{\text{wast}} \geq 0 \quad (15)$$

The CHP performance coefficients a and b , which have been obtained using linear regression, are used to estimate the fuel input F_{CHP} , power output $G_{\text{CHP_el}}$ and thermal output $G_{\text{CHP_th}}$ of the CHP engine as functions of the part load output. The binary variable y_{CHP} is again used so that F_{CHP} , $G_{\text{CHP_el}}$ and $G_{\text{CHP_th}}$ are set to 0 when the engine is off:

$$F_{\text{CHP}} = a_f \cdot pl_{\text{CHP}} + b_f \cdot y_{\text{CHP}} \quad (16)$$

$$G_{\text{CHP_el}} = a_{\text{el}} \cdot pl_{\text{CHP}} + b_{\text{el}} \cdot y_{\text{CHP}} \quad (17)$$

$$G_{\text{CHP_th}} = a_{\text{th}} \cdot pl_{\text{CHP}} + b_{\text{th}} \cdot y_{\text{CHP}} \quad (18)$$

The optimisation problem is expressed in equation 19, where pl_{CHP} and y_{CHP} are the decision variables:

$$\max_{pl_{\text{CHP}}, y_{\text{CHP}}} [S_{\text{tot}}] \quad (19)$$

subject to constraints 10-18. The full mathematical formulation is detailed in the work of Olympios *et al.*

TRIAL OUTLINE

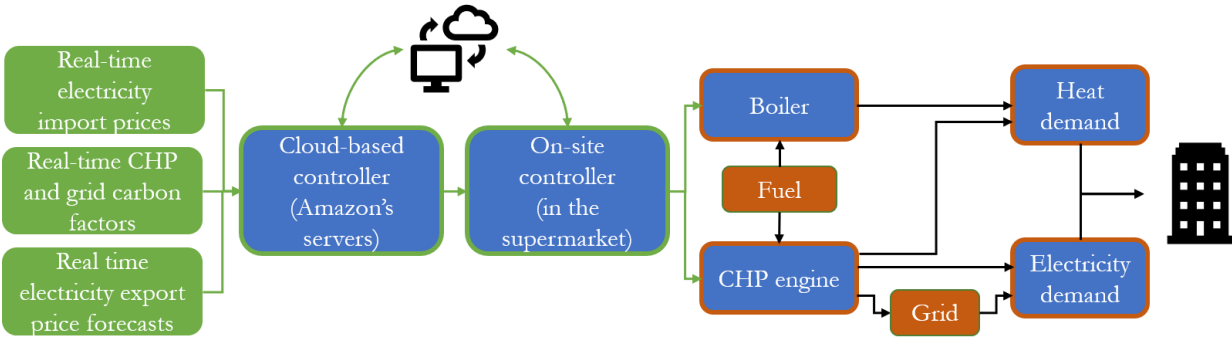


Figure 1 Schematic representation of CHP setup and operation (adopted from the work of Olympios *et al.*).

A schematic representation of the optimiser technology is shown in Figure 1. The optimiser allows electricity price forecasts to be considered in the CHP unit operation. Exported energy can be maximised during high export tariffs and similarly imported energy can be minimised when favourable.

The cloud-based controller works through the Amazon Web Service, utilising its servers to provide substantial cost reduction over traditional non-cloud-based methods. The software communicates with the on-site controller, setting the part load output for the engine, with the on-site controller subsequently maintaining the unit at that point.

The optimiser has been installed on a real CHP unit operating in a UK supermarket to validate the results of initial simulations. The costs of operation and implementation of the technology are detailed in Table 1 and store specifics for the trial installation are detailed in Table 2.

Table 1. Installation and implementation costs for the optimiser.

Cloud Cost (USD)	Professional Optimiser Coding (USD)	Installation Cost (USD)	Electricity Market Database (USD)
\$6.50 /month/store	\$227,500	\$12,357 /store	\$6,500 /year

Table 2. Store specifics for optimiser trial before installation.

Store Size	CHP Unit Size	Av. Electricity Demand During Trading Hours	Av. Heat Demand During Trading Hours	Electricity Cost (USD)	Heat Cost (USD)
1856 m ²	250 kW _{elec}	100 kW	56 kW	\$41,750 /yr	\$68,520 /yr

The optimiser solution developed controls the CHP unit in real-time, generates savings and then outputs the key performance indicators (KPIs) to a Grafana observability platform. A screenshot of the platform is shown in Figure 2. Of the nine KPIs tracked and visualised on the Grafana platform, the crucial two are the ‘BaU 24hr Cost (£)’ and the ‘Actual 24hr Cost (£)’. The discrepancy between these two values indicates the 24hr savings that the optimiser generates. Unfortunately, on the day the screenshot was taken, the optimal output was the same as BaU, showing how cost savings are highly dependent on store-specific factors and electricity prices. The other KPIs tracked on the platform give an indication of how the store, CHP unit and optimiser are operating. Electricity prices, which are the most crucial factor influencing the optimiser part load output, are also included.



Figure 2 Grafana observability platform visualising live KPIs for CHP performance with the optimiser. Left side labels (top to bottom): ‘BaU 24hr Cost (£)’, ‘CHP Efficiency’, ‘Real Time Costs (£/hr)’, ‘Electricity Prices (£/MWh)’. Right side labels (top to bottom): ‘Actual 24hr Cost (£)’, ‘Real-Time CHP Gross Power Output (kW)’, ‘CHP Operation (kW_{elec})’, ‘Carbon Intensity (gCO₂/kWh)’. Bottom label: ‘Store Operation (kW)’.

TRIAL RESULTS

The optimiser minimises costs based upon import/export energy volumes and energy prices. Energy data from the local meter is therefore used, and energy prices are comprised of predicted ‘day-ahead’ wholesale price, and both predicted and defined regional tariff charges. To validate the optimiser results, the export energy volumes and revenue streams are compared with the August 2019 bill from the trial site, with results shown in Table 3.

Table 3. Comparison of metered energy volume, and related revenues, for; the bill, the optimiser data and, the bill meter volume using optimiser prices.

	Metered Volume (kWh)	Export Revenue (USD)	BSUoS Predicted (USD)	GDUoS June '19 (USD)	Reactive (USD)	Total (USD)
From Bill	26.95	\$1,370	\$118	\$98	\$3	\$1,583
Optimiser	30.37	\$1,559	\$62	\$95		\$1,716
Data	+13%	+14%	-48%	-3%	-	+8%
Optimiser	26.95	\$1,362	\$55	\$101		\$1,518
Prices	+0%	-1%	-53%	+4%	-	-4%

The export meter is poorly calibrated, meaning the metered volume is 13% greater than the bill value provided, though the total savings are only 8% greater. As meter calibration can be corrected, the price profiles used by the optimiser are applied to the bill export energy volumes. This results in total savings 4% lower than the bill, primarily due to under prediction of Balancing Services Use of System (BSUoS) charges. BSUoS prices are back-calculated, so the official predictions released by the national grid are the best estimate available. The error in export revenue is due to small differences in the wholesale price, whilst the Generation Distribution Use of System (GDUoS) error is due to reactive charges being neglected. Reactive charges are challenging to predict and both GDUoS and overall reactive charges together comprise only 0.4% of the total, well within the margin for error. Further investigation into developing more accurate BSUoS predictions may however be warranted.

The results from the trial site are also compared with optimiser simulation model results, giving a 6.4% under-prediction of overall system costs. The conservative estimation in savings is positive for getting project approval, and

matches with the outputs of the bill validation. The price forecasts have since been revised, providing improvement to the 4% under-prediction demonstrated in bill validation. Non-linear CHP behaviour is also likely to have some impact.

SIMULATION RESULTS

Having validated, within acceptable error margins, both the optimiser and the model, the model is applied to three case study sites. These were selected based upon the average daytime load (ADL), defined as the store's electricity consumption divided by CHP maximum output. To understand the impact of sizing on the savings achievable with the optimiser, stores with a range of ADLs are selected. Heat demand, electricity demand, import/export electricity prices and CHP specifications are required as inputs to the model. Table 4 shows the ADLs for the three case study stores, along with the financial analysis of the simulation results.

Table 4. Financial analysis of results from running the model both with and without the optimiser, for stores A, B and C respectively. CHP unit size given in column one.

Store Details	Av. Daytime Load		Export Revenue (USD)	Import Cost (USD)	Fuel Cost (USD)	Total Cost (USD)	Savings (USD)
Store A		No Opt	\$17,254	\$41,750	\$68,524	\$93,020	\$2,219
250 kW	43%	Optimiser	\$28,262	\$29,407	\$89,655	\$90,800	(2%)
Store B		No Opt	\$3,039	\$113,565	\$140,368	\$250,895	\$29,233
400 kW	75%	Optimiser	\$25,360	\$0	\$247,022	\$221,662	(12%)
Store C		No Opt	\$0	\$175,444	\$98,480	\$273,924	\$20,079
210 kW	138%	Optimiser	\$0	\$61,396	\$192,451	\$253,847	(7%)

The optimiser always generates financial savings relative to the simple load-following control system used for the baseline, which is the expected result. However, the ADL is crucial in determining the extent of savings achievable. Savings are generated either via exporting during periods of high export price, mainly during the afternoon, or operating the CHP overnight, when the baseline control system has the unit off. Figure 3 shows that the electricity import prices are significantly higher than the export prices, making avoiding importing particularly lucrative. Figure 4 shows the part load graphs, with and without the optimiser, as well as the electrical power profiles for stores A, B and C respectively.

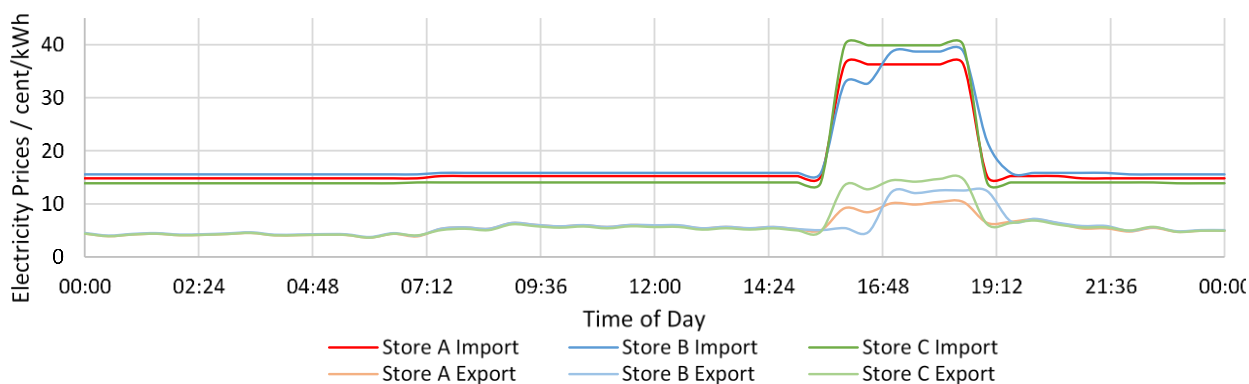


Figure 3 Graph showing winter weekday import and export prices for stores A, B and C respectively.

Store A

- Lowest cost savings of 2% as the oversized CHP unit has limited flexibility to utilise full optimiser capabilities.
- Night operation unfeasible due to 0.65 minimum part load.
 - Low overnight exporting prices make exporting unfavourable.
 - Overnight electricity demand far below minimum CHP output to generate sufficient import savings.

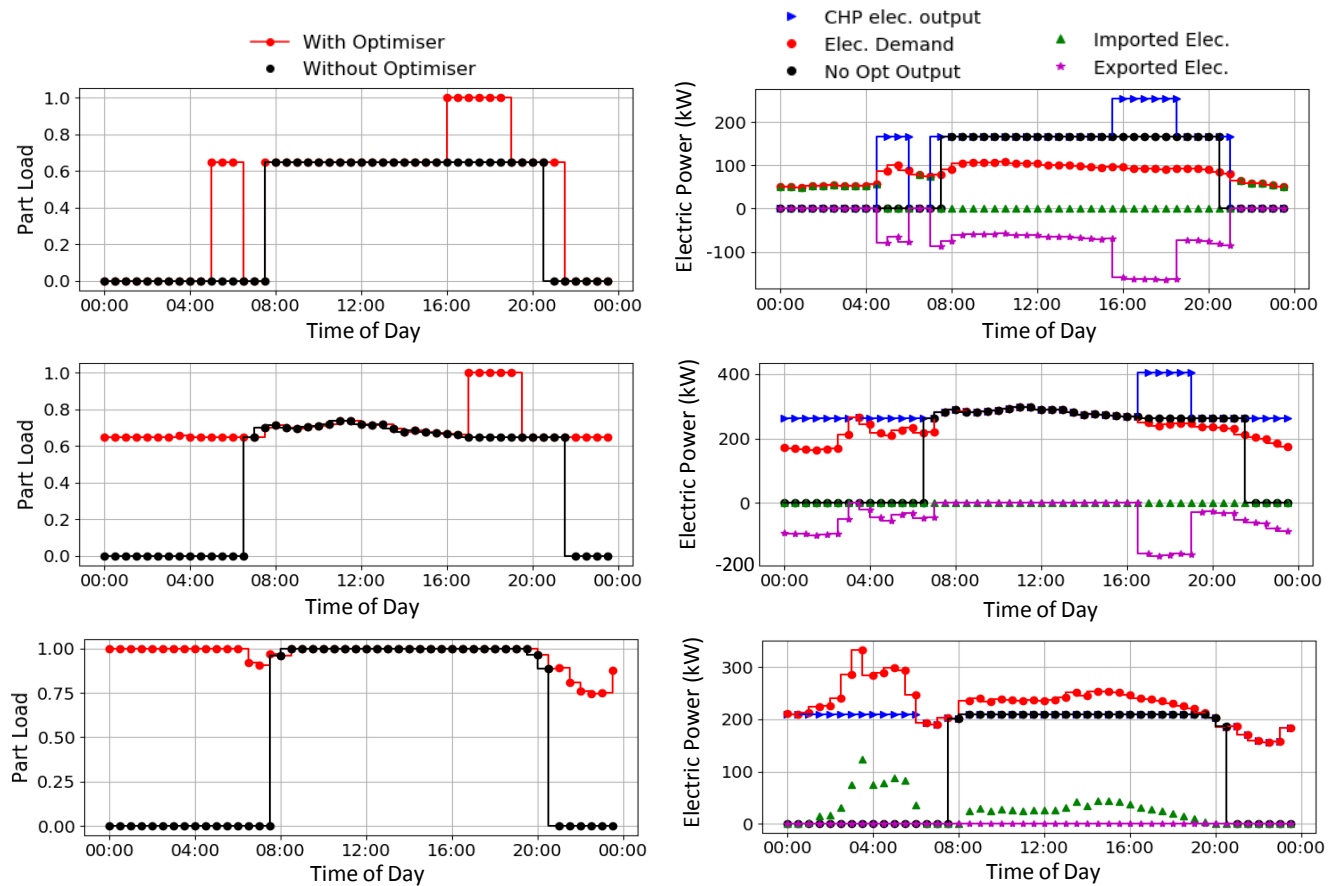


Figure 4 Graphs showing the winter weekday daily profiles for CHP part load output (left) and electrical power (right), for stores A, B and C respectively (top to bottom).

Store B

- Largest cost savings of 12% as CHP unit well sized at approx. 75% of ADL.
 - Optimiser has maximum flexibility to generate savings.
- Operation throughout the night as the electricity demand is always sufficient to make avoiding import costs optimal.
 - Electricity demand below the minimum part load, necessitating electricity export overnight, with low export prices.
 - Import prices being significantly higher than export drives this strategy.

Store C

- Only 7% cost savings achievable as the undersized CHP unit has limited flexibility to utilise full optimiser capabilities.
 - No export revenue as CHP is at maximum capacity when export prices are high.
 - Always load-follows the stores electricity demand.
- Identical CHP operation as with the baseline control system, with relative savings generated from overnight operation.
- Best option is to allow the existing control system to operate without turning off overnight.
 - Whether benefits available from the optimiser dependent primarily on CHP sizing.

Though savings are generated at all sites, the waste heat produced in excess of the store heating demand is a concern. Unfortunately, large-scale, widespread heat supply networks are not currently in place in the UK, though as of January 2018, approximately 2% of the UK's heat demand was met via smaller localised networks (ADE, 2018). Additionally, in the five preceding years the number of networks increased by 750%, indicating significant investment. The Government's Heat Network Development Unit also shows the existence of the necessary political will to pursue heat supply networks (Department of Energy and Climate Change, 2013). These networks are also most applicable to densely populated areas, in which the majority of supermarkets are located, likely making monetisation of this heat feasible in the future. Selling the excess heat to these networks is therefore likely to increase the savings generated by the optimiser. Prior to the establishment of the heat supply networks, it may be worthwhile to increase winter space heating set points in the store to utilise some of the excess heat. This is likely to increase customer comfortability, encouraging them to remain longer in store, increasing the average spend.

Table 5. Waste heat and CO₂ emissions results from running the model both with and without the optimiser, for stores A, B and C respectively. CHP unit size given in column one.

Store Details	Av. Daytime Load		Waste Heat (MWh)	Waste Heat Increase	CO ₂ Emissions (tonnes/year)	Change in CO ₂ Emissions
Store A		No Opt	735		438	
250 kW	43%	Optimiser	1,032	48%	428	-2% (-24%)
Store B		No Opt	1,261		926	
400 kW	75%	Optimiser	2,716	144%	1,262	+36% (+7%)
Store C		No Opt	872		813	
210 kW	138%	Optimiser	2,277	196%	1,139	+40% (+5%)

Table 5 shows a small emissions reduction for store A when using the optimiser, but stores B and C show significant increases. The extra emissions are due to grid electricity now having a lower carbon factor than from the CHP, fed with natural gas. However, utilisation of the waste heat would offset the increase in carbon emissions, by removing load from gas boilers. The change in emissions with the optimiser, when all heat produced is usefully used, falls to -24%, 7% and 5% for store A, B and C respectively, shown in brackets in Table 5. A viable solution is also to use biogas, though demand is currently outstripping supply, limiting its utility (IGU, 2015). Furthermore, an additional constraint may be added to the optimiser, limiting the emissions increase to a level deemed acceptable.

DISCUSSION

The analysis above clearly demonstrates the financial feasibility of optimiser installation and the significant savings available. However, local store and CHP characteristics lead to large variation in available savings. The first stores selected for optimiser installation should have an ADL within the operating range of the CHP unit, between part loads of 0.65 and 1. This will enable the optimiser maximum flexibility to generate savings, however the unit size is also crucial as optimiser installation cost is not dependent on the CHP size. Therefore, a large depot site, with an undersized CHP unit, may actually provide shorter payback times than a well-sized CHP in a smaller supermarket store. This illustrates the benefit of the model in allowing optimisation considering all the various factors and indicating where the greatest financial savings are available. This includes the significant variation in prices by distribution network operator location within the UK, which are particularly challenging to assess for impact on savings generated by the optimiser.

A number of issues arose with the initial pilot installation, particularly in relation to project management. Multiple contractors were required to carry out the works and ensuring adequate communication was extremely challenging. It was difficult to coordinate the different contractors on such a multidisciplinary project and keep the focus on the delivery of the overall solution rather than each single work package. A further issue was 'legacy costs' resulting from poor documentation of the initial CHP installation, and any subsequent services. This necessitates significant work to understand the current state of the system, and so the work required for installation. It became clear that for the successful delivery of such projects, good asset documentation is essential.

Though installation and implementation costs are generally consistent across sites, some local complications are likely to exist. These may include; lack of space for instrumentation; operational constraints imposed by stakeholders involved, which would require additional hardware or software and; lack of specific skills among the contractors.

CONCLUSION

This paper introduces a novel, cloud-based CHP optimiser technology with KPIs output to a Grafana observability platform. The optimiser incorporates electricity prices, heat demand and electricity demand into determining the CHP output, and has been installed in a real UK supermarket. Applying the model in three case study supermarkets shows to provide cost savings between 2% and 12%, with only modest investment costs in software and infrastructure. CHP units sized within the feasible operating range, above a part load output of 0.65, generate the greatest savings, as the optimiser has the greatest flexibility. However, larger units, even though less nearly optimal, may generate greater overall savings and may therefore be targeted for optimiser implementation. Although installation costs are not expected to vary greatly from site-to-site, the installation of the real-time controller in some stores show no material improvement over the existing control systems, demonstrating the value of the pre-feasibility analysis using the optimiser. Though waste heat does increase significantly with all strategies, the propensity to sell this heat within the UK is likely to improve in the near future, therefore enhancing the outlook of carbon emissions.

ACKNOWLEDGMENTS

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NOMENCLATURE

CHP = Combined Heat and Power
BaU = Business as Usual
ADL = Average Daytime Load
KPIs = Key Performance Indicators
BSUoS = Balancing Services Use of System
GDUoS = Generation Distribution Use of System

REFERENCES

- Acha, S. (2013) 'Modelling distributed energy resources in energy service networks', *Modelling Distributed Energy Resources in Energy Service Networks*, pp. 1–208. doi: 10.1049/PBRN016E.
- Acha, S. *et al.* (2018) 'Optimal design and operation of distributed low-carbon energy technologies in commercial buildings', *Energy*, 142, pp. 578–591. doi: 10.1016/j.energy.2017.10.066.
- ADE (2018) *Market Report: Heat Networks in the UK*, *The Association for Decentralised Energy*. Available at: [https://www.theade.co.uk/assets/docs/resources/Heat Networks in the UK_v5 web single pages.pdf](https://www.theade.co.uk/assets/docs/resources/Heat%20Networks%20in%20the%20UK_v5_web_single_pages.pdf).
- Beith, R. (2011) *Small and micro combined heat and power (CHP) systems, Small and Micro Combined Heat and Power (CHP) Systems: Advanced Design, Performance, Materials and Applications*. Woodhead Publishing Limited. doi: 10.1533/9780857092755.
- Department of Energy and Climate Change (2013) 'The Future of Heating : Meeting the challenge', *Dec*, (March). Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/190149/16_04-DECC-The_Future_of_Heating_Accessible-10.pdf.
- IGU (2015) 'Biogas - From Refuse to Energy', p. 20. Available at: [https://www.igu.org/sites/default/files/node-page-field_file/IGU Biogas Report 2015.pdf](https://www.igu.org/sites/default/files/node-page-field_file/IGU%20Biogas%20Report%202015.pdf).
- Maschuch, J. *et al.* (2018) 'Experimental development of a kilowatt-scale biomass fired micro – CHP unit based on ORC with rotary vane expander', *Renewable Energy*. Pergamon. doi: 10.1016/J.RENENE.2018.08.113.
- National Grid (2018) *Summer Outlook Report*. Available at: <https://www.nationalgrid.com/document/111936/download>.
- Olympios, A. *et al.* (2019) 'Installation of a dynamic controller for the optimal operation of a CHP engine in a supermarket under uncertainty', in *The 32nd International Conference on Efficiency, Cost, Optimisation, Simulation and Environmental Impact of Energy Systems*.
- Sundberg, G. and Henning, D. (2002) 'Investments in combined heat and power plants: influence of fuel price on cost minimised operation', *Energy Conversion and Management*. Pergamon, 43(5), pp. 639–650. doi: 10.1016/S0196-8904(01)00065-6.
- Yu, D. *et al.* (2017) 'Sizing combined heat and power units and domestic building energy cost optimisation', *Energies*, 10(6). doi: 10.3390/en10060771.