Modelling of Mine Shaft Thermal Energy Storage (MSTES) for District Heating (DH) and Grid Balancing

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ABSTRACT

This paper investigates the potential for water filled mineshafts or similar storage structures to provide flexibility and improve financial performance. A techno-economic model and case study are described and Heat Pump (HP) and CHP based DH systems evaluated. Future electricity tariffs with import and export pricing based on wind generation surplus and shortfall periods, and costs for CHP fuels (e.g. hydrogen) are considered. Temperatures in MSTES and surrounding geology are modelled. MSTES integration was found to have levelised cost of heat (LCOH) advantages. With MSTES both HP and CHP based DH systems can offer up to 100% flexibility for grid balancing.

Keywords: District heating; Thermal energy storage; Combined heat and power; Heat pump; Mine shaft.

INTRODUCTION

Mineshafts and subsurface mining infrastructure can be used for district heating (DH) and balancing renewable power grids using heat pump (HP) and combined heat and power (CHP) plants (Huang et al., 2023; Matas-Escamilla et al., 2023; Vokurka & Kunz, 2022). Mineshafts near population centres have potential benefits for thermal energy storage (TES), including high volume, low surface footprint, surface access, and consistent materials (Al-Habaibeh et al., 2018; Chudy, 2022).

The future renewable grid is predicted to provide cost benefits for control and storage, increased flexibility in energy balancing markets, and encourage smart controls. (Lyden & Tuohy, 2022; Sifnaios et al., 2023; Howorth et al., 2023). HPs are gaining popularity for their ability to effectively distribute renewable heat while also giving flexibility to the electrical grid (Lamb & Elmes, 2024). HPs rely on thermal energy extracted from natural sources such as air, earth, and water (Wang et al., 2022). HP and TES can add flexibility to energy markets, decreasing the requirement for costly clean backup production (Ołtarzewska & Krawczyk, 2024). Drammen and Queens Quay DH systems employ heat pumps ("Drammen District Heating Case Study," n.d.; "Queens Quay District Heating," n.d.).

CHP systems integrated can supply renewable heat (e.g. green hydrogen or renewable waste to energy) and flexibility support to the grid by running preferentially in low wind or low frequency conditions.

This paper investigates the potential flexibility and cost benefits of MSTES or other similar storage integration in district heating within renewable grids.

METHOD

First, conceptual systems and a case study are defined that support investigation of MSTES integration in HP and CHP based DH in the future renewable grid. Then, a modelling base is described, KPIs defined, parametric investigation carried out, and results presented.

CONCEPTUAL SYSTEMS AND CASE STUDY

The study is based on mineshafts in the UK, specifically Barony (*Barony | Coal and Community*, n.d.) and Monktonhall (*Monktonhall Colliery | Canmore*, n.d.). Barony has concrete-lined vertical shafts of 7m diameter, with up to 23,000 m^3 available as MSTES.

A District Heating demand profile for 1632 UK dwellings was assumed, with a 50 °C supply and a 30 °C return (Lyden & Tuohy, 2022; Secretary, n.d.; "West Whitlawburn Housing Co-Operative District Heating," n.d.; Zhang et al., 2022).

33 kV wind generation and electricity demand data for the East Ayrshire region of the UK was used to represent a future wind-based grid (Figure 1). A 2-tariff pricing model based on surplus and shortfall periods was used to represent incentivized flexibility, shown for an illustrative 3-day period in Figure 2 (the same 3 day winter period is used to show the system behaviour throughout the paper).

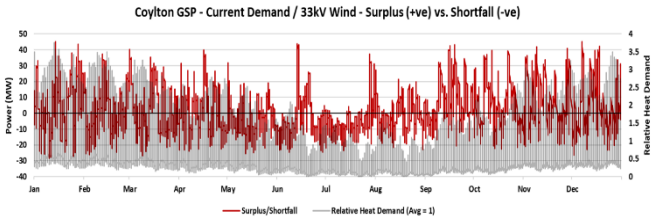

Figure 1: Relative wind surplus and shortfall (red) and relative heat demand (grey) for East Ayrshire.

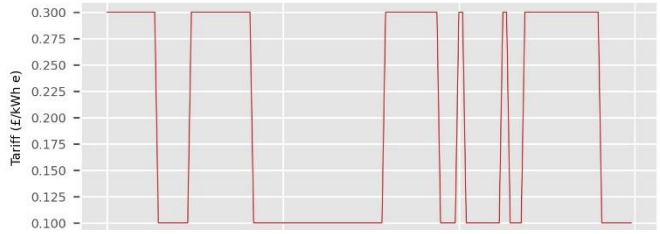

Figure 2: Exemplar 3 days in winter: import tariff with 10p/30p per kWh rates for surplus/shortfall periods.

A conceptual system with MSTES in a HP-based DH system was developed (Figure 3). In the study the HP was sized to meet peak load so backup heaters were not used, the HP operated to meet the heat demand and charge the store during wind surplus periods, only operating in wind shortfall periods when the store on its own was not sufficient.

Similarly, a conceptual system with MSTES in a CHP-based DH system (Figure 4) was developed. CHP was sized to meet the peak load, the CHP operated to provide grid support in wind shortfall periods and the backup boiler used to meet heat demand during wind surplus periods if the store was not sufficient.

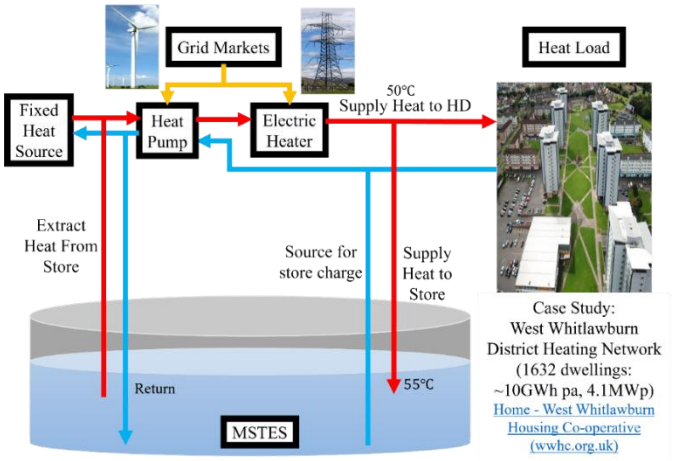

Figure 3: High level concept for the HP based system

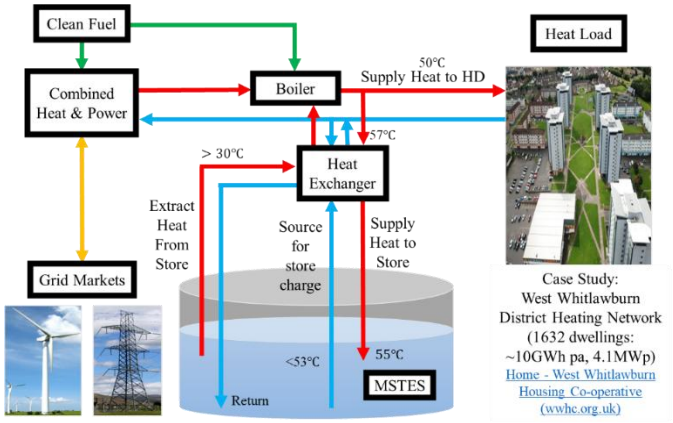

Figure 4: High level concept for the CHP based system

MODEL

An overall system model was developed from PyLESA with rule-based controls *(Lyden & Tuohy, 2022)*. A new MSTES model was adapted from the PyLESA thermal storage tank. Standard tank heat loss parameters were replaced by heat transfer to the shaft lining and surrounding geology using standard borehole models *(Katsura et al., 2020)*.

Nodes with appropriate physical properties extended horizontally from the centre of the shaft to a radius of 1000m (Figure 5). The horizontal nodes were replicate vertically in 10 layers to represent vertical temperature variations. An equivalent model in COMSOL gave comparable sub surface temperature results (RMSE% < 2%).

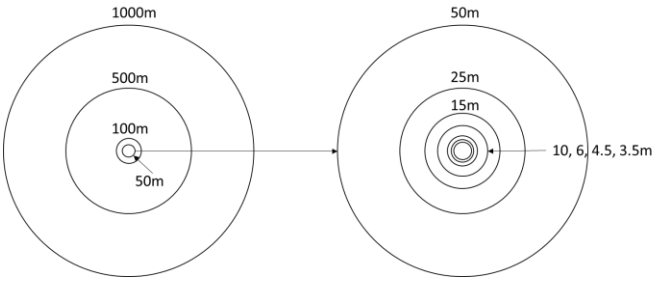

Figure 5: Horizontal layers / nodes representing shaft lining and surrounding geology in the MSTES model.

KEY PERFORMANCE INDICATORS (KPI)

HP based systems can bias their operation to periods of wind surplus; equation 1 defines the KPI used to measure the percentage of flexibility delivered by a HP based system.

CHP based systems can bias their electricity production to periods of grid shortfall; equation 2 provides the KPI for flexibility provision from a CHP based system. In this study the controls are set to hold off the CHP in wind surplus periods and use only the backup boiler, so Flex%(CHP) = 100%.

Levelised Cost of Heat (LCOH) from BEIS (equation 3) was used (Lyden & Tuohy, 2022; Yang et al., 2021) with a discount rate of 5%. LCOH in this definition refers to the minimum selling price to be received by the operator of the heat production system. Capital costs are determined according to (Yang et al., 2021). Capital cost of MSTES/m3 was assumed to decrease exponentially with volume according to the CAPEX of large-scale water tanks (*Technology Catalogues*, 2016). Capital values are as follows: HP_{CAPEX} = £600/kW (*IRENA*, 2022), CHP_{CAPEX} = £4000/kW (*IRENA*, 2020), B_{CAPEX} = £100/kW (boiler (B) only included for the CHP case). Operational Maintenance (OM) was 2% of the capital cost. OP includes fuel import cost minus income generated by CHP exports.

$$\text{Flex\%(HP)} = \frac{HP\ electricity\ used\ in\ wind\ surplus}{Total\ HP\ electricity\ used} \times 100\% \quad (1)$$

$$\text{Flex\%(CHP)} = \frac{CHP\ electricity\ generation\ in\ wind\ shortfall}{Total\ CHP\ generation} \times 100\% \quad (2)$$

$$LCOH_{BEIS} = CAPEX + \sum_{t=1}^{n} \frac{OP+OM}{(1+d)^t} / \sum_{t=1}^{n} \frac{Et}{(1+d)^t} \quad (3)$$

INVESTIGATION, RESULTS, DISCUSSION

The study investigated MSTES behaviour in terms of: shaft and surrounding geology temperatures over a 10-year time horizon, detailed system performance was illustrated for the same 3 day period shown in figure 2, and the overall Flex and LCOH KPIs calculated.

Physical input parameters varied included: store temperature set points (between 30°C and 70°C), volume of shaft utilised (7m diameter shaft with utilised water depths between 100 m and 600 m).

Financial input parameters varied included: electricity import tariff (during wind surplus periods fixed at 10 p/kWh, and varied between 10p and 120p during wind shortfall periods); electricity export tariff (revenue from CHP exports, varied between 10p and 120p in wind shortfall periods); and CHP/Boiler fuel cost varied between 7.5p/kWh and 37.5p/kWh representing current fossil gas and future green hydrogen prices.

MSTES Performance

Resulting water temperatures for HP and CHP based systems with 55 ℃ store temperature set point and a 200 m utilised water depth in the first 2 years of operation are shown in Figures 6 and 7 (top (L1), middle (L5) and bottom (L10)). The initial heating up period was short, around 2 months for both cases. The CHP based system has higher temperatures for the case study consistent with slightly longer operational hours (wind shortfall periods) for the East Ayrshire grid scenario used.

Resulting ground temperatures are shown in Figure 8 for the CHP system with a 55℃ 200m store. Again, the shaft and surrounding geology had higher average temperatures for the CHP system.

The heat injected into the ground is effectively lost to the system. Losses are greater in earlier years. The losses over a 10 year horizon were calculated (equation 4, figure 9). Results indicated that losses increased with temperature and volume but appear reasonable in comparison to other storage technologies.

$$Storage\ losses = \frac{Heat\ loss\ from\ store\ to\ surrounding}{Heat\ charged\ to\ store} \times 100\% \quad (4)$$

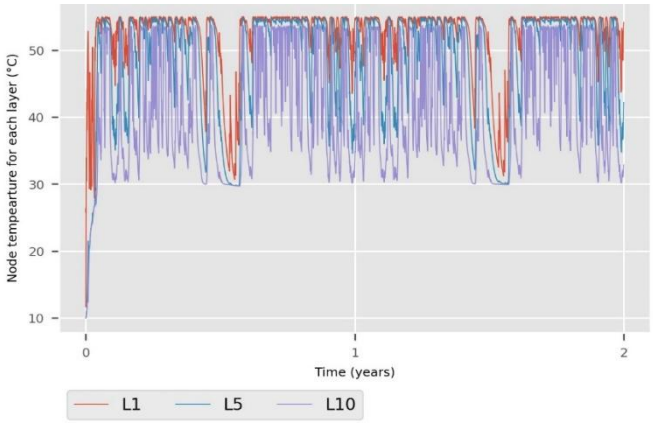

Figure 6: Shaft water temperatures for HP 55 ℃ 200 m Store over the 1st 2 years of operation.

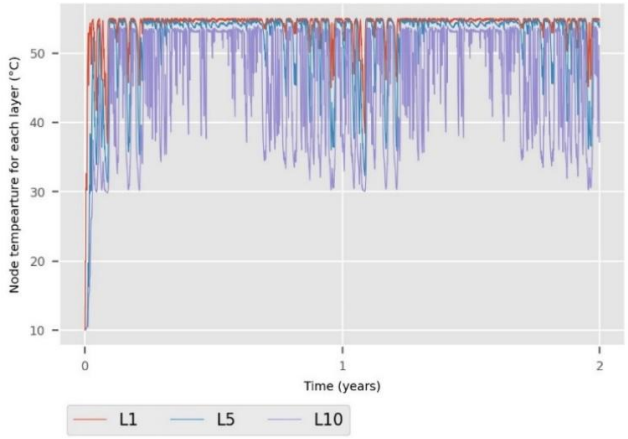

Figure 7: Shaft water temperature for CHP 55 ℃ 200 m Store over 1st 2 years of operation.

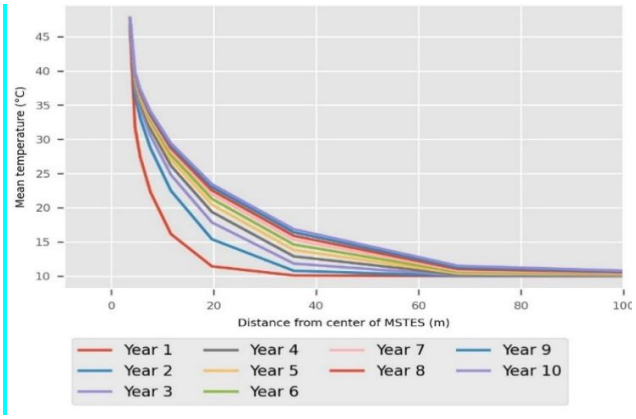

Figure 8: CHP 55℃ 200m node temperature for surrounding geology over a 10 year period.

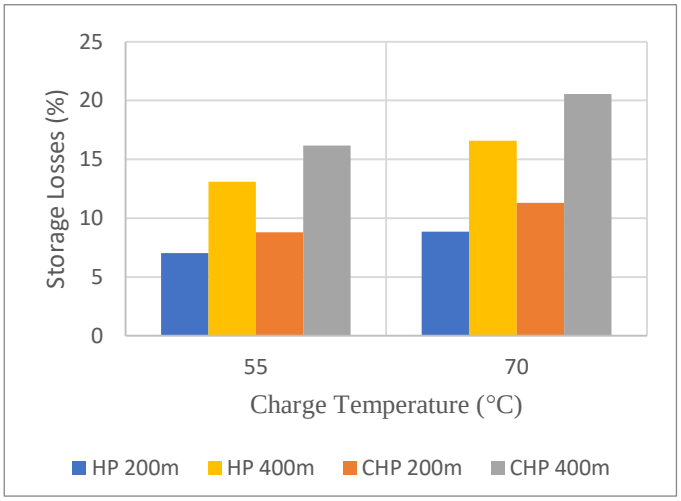

Figure 9: 10 year losses vs temperature set point and store size for HP and CHP systems.

HP Based System Performance

The HP 55 ℃ 200 m system behaviour is illustrated in Figure 10 (shaft water temperatures) and Figure 11 (electricity consumption) over the three-day period from figure 2. It can be seen that during wind surplus the heat pump runs fully on with the heat supplying demand plus charging the store; and during wind shortfall the heat pump only operates as a temperature top-up when the store temperature drops below the heating delivery temperature.

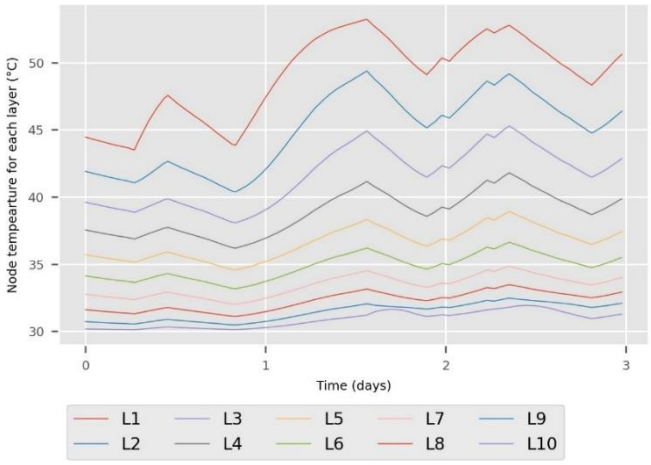

Figure 10: Shaft water temperatures for the 10 MSTES nodes for HP 55°C 200m system (same 3 days as fig 2).

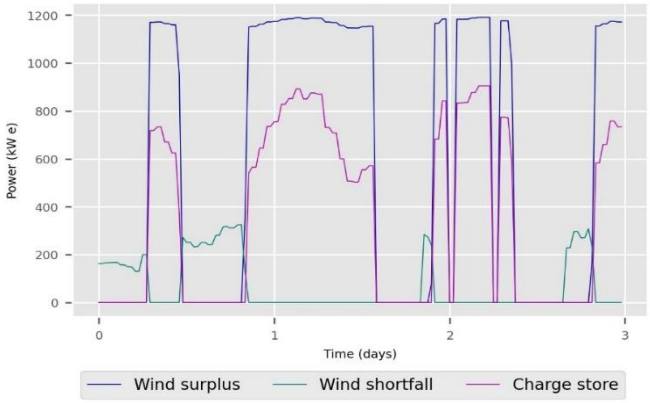

Figure 11: Electricity use in HP 55°C 200m system (exemplar 3 days)

The HP based system without MSTES has to operate when there is heat demand and only 47% of the electricity consumed is from grid surplus periods. MSTES integration in HP systems supports preferential operation in surplus periods and correspondingly increases in Flex%(HP) however the store set point temperature needs to be greater than the heat delivery temperature to give high levels of flex support to the grid (figure 12). Note: this higher temperature store set point reduces HP efficiency slightly.

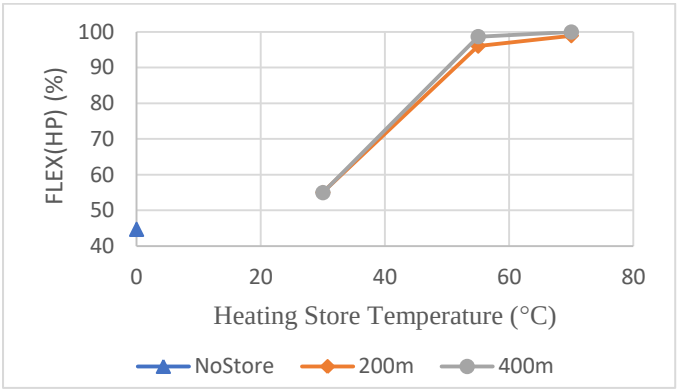

Figure 12: Flex%(HP) for HP 200m and 400m MSTES vs. no MSTES.

MSTES in HP systems supports use of lower cost electricity in wind surplus at the expense of increased system capital cost. MSTES integration provided overall LCOH advantages, even for higher store temperatures, where the tariff penalty for use in wind shortfall periods was greater than approximately 2x (i.e. >20p/kWh, figure 13). The advantage of MSTES becomes greater with increasing wind shortfall electricity costs, largely protecting LCOH for HP+MSTES systems while HP only DH systems would see significant LCOH increases.

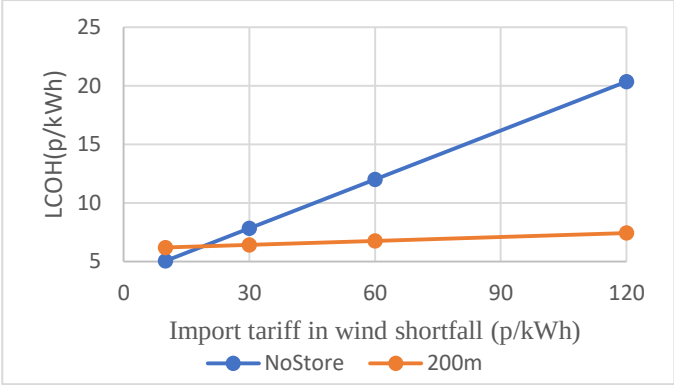

Figure 13: LCOH for HP 55°C 200m system with MSTES vs. no MSTES.

CHP Based System Performance

CHP+boiler systems can provide Flex%(CHP)=100%, MSTES integration can still be beneficial in enabling better utilisation of heat and reducing the quantity of fuel used.

Currently CHP operation is often continuous with dumping of heat being financially advantageous due to fuel cost vs. electricity revenue. This paradigm is expected to change in future with electricity exports being incentivised during wind shortfall periods, clean CHP and boiler fuel costs increasing, and potential legislation requiring that CHP heat is not dumped to the environment.

Here, two situations are presented: (i) The CHP system operates at maximum capacity, known as 'power mode', only when the export tariff is high. During other times, the stored heat plus backup boiler meet the heat demand; or (ii) The CHP system operates in 'heat mode' running during periods of high export tariff modulating its operation to prevent excess heat, the store and backup boiler supply the heat in wind surplus periods.

Figure 14 displays MSTES water node temperatures for the exemplar 3-day period, store charging occurs during wind shortfall periods (unlike the HP case where store is charged in wind surplus periods). The CHP system runs only when electricity prices are high.

Figure 15 and 16 show the CHP fuel use, electricity export, and useful heat export (i.e. the heat used to meet demand plus charge the store, excluding dumped heat) for the exemplar 3 days for CHP in 'power mode' and 'heat mode' respectively.

Day 1 clearly illustrates the difference between the two modes, the CHP runs full capacity during the wind shortfall periods in 'power mode' (dumping surplus 'non useful' heat when the store is full), while the CHP is moderated to meet the useful heat demand (store plus end user) in 'heat mode', reducing fuel used and also electricity output.

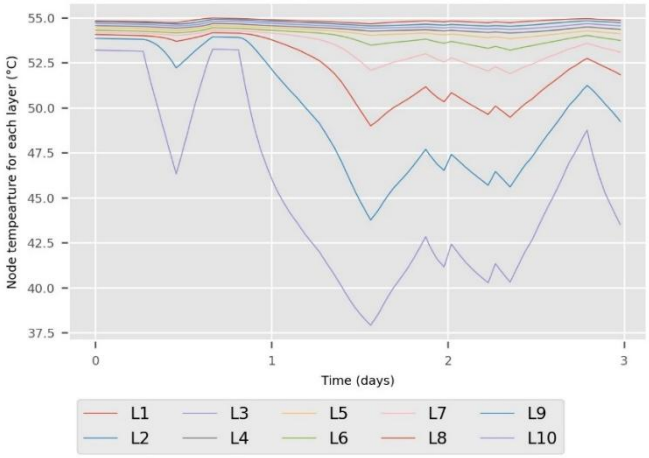

Figure 14: MSTES water node temperatures for CHP 55°C 200m system (exemplar 3 days)

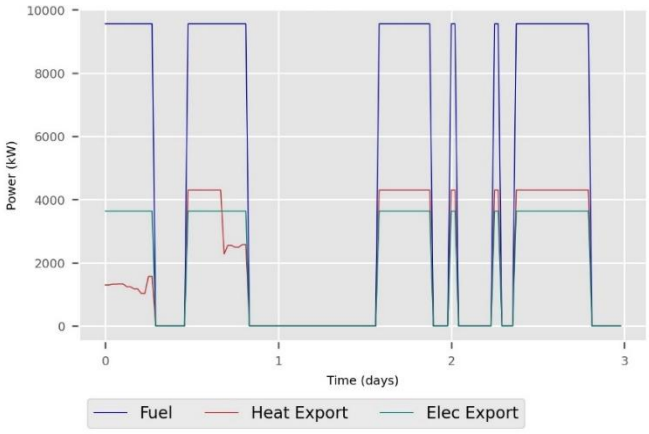

Figure 15: Energy flows for CHP(power mode) 55°C 200m system (exemplar 3 days)

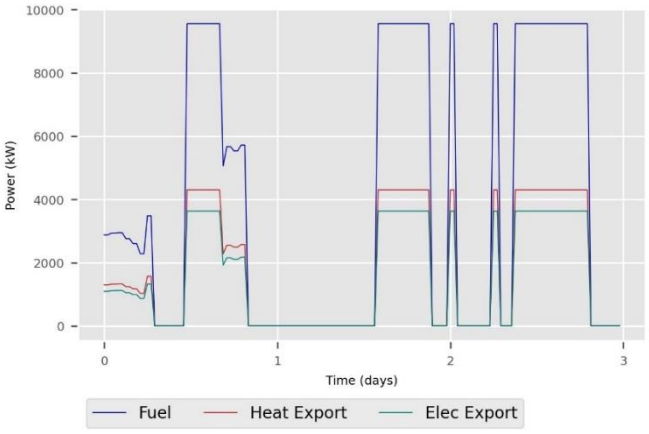

Figure 16: Energy flows for CHP(heat mode) 55°C 200m system (exemplar 3 days)

For the CHP based system LCOH is highly dependent on fuel cost and revenue from electricity exports.

In 'power mode' the reduction in fuel use realised through MSTES for 7.5p/kWh fuel cost does not improve LCOH significantly (figure 17), and MSTES integration would not appear to be justified in this case. However if fuel costs were 37.5p/kWh then there are significant LCOH benefits (figure 18). At the high fuel cost there would need to be a high electricity export tariff to give an LCOH comparable to a HP based system.

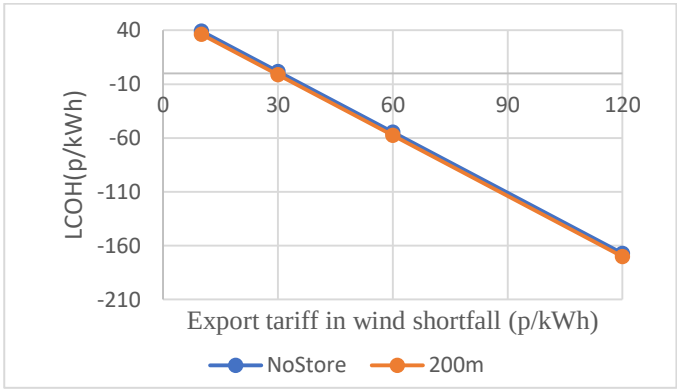

Figure 17: LCOH for CHP(power) with 7.5p/kWh fuel

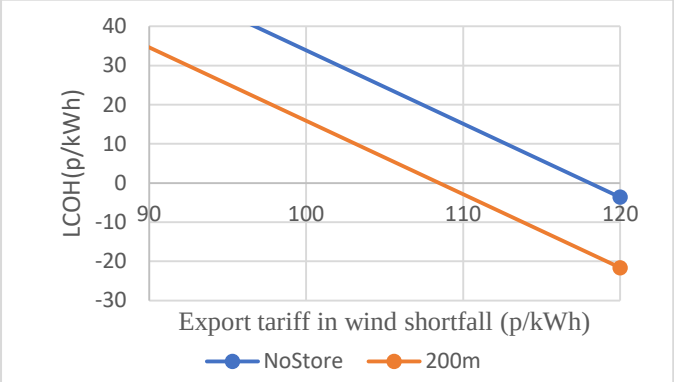

Figure 18: LCOH for CHP(power) with 37.5p/kWh fuel

When the system operates in 'heat mode' with no dumping of heat then MSTES charging allows increased operation in low wind periods compared to no MSTES where the CHP must modulate to meet only the DH demand. This increased revenue in addition to fuel saving means MSTES integration can give an improved LCOH even in the low cost fuel case (figure 19). For higher cost fuel the export tariff must be high in wind shortfall periods to give competitive LCOH (figure 20).

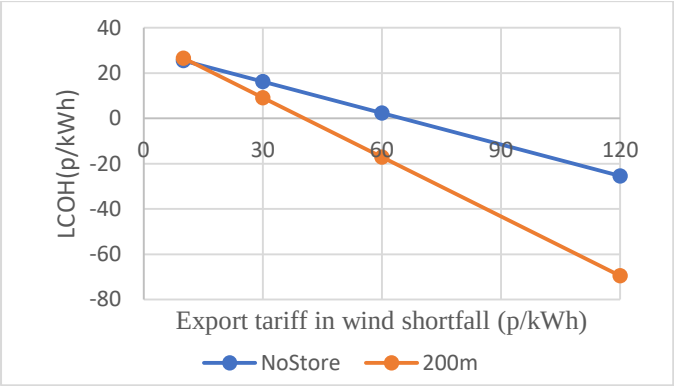

Figure 19: LCOH for CHP(heat) with 7.5 p/kWh fuel

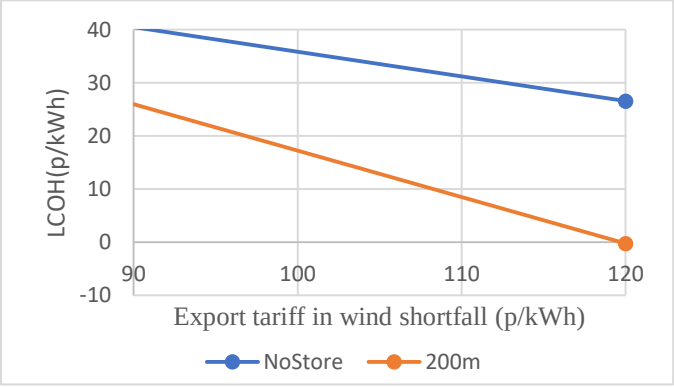

Figure 20: LCOH for CHP(heat) with 37.5 p/kWh fuel

CONCLUSIONS

A techno-economic model and case study are described and then the performance of district heating with and without MSTES evaluated across a range of scenarios. Future electricity tariffs with import and export pricing based on grid wind generation surplus and shortfall periods, and future costs for low carbon CHP fuels are considered. The results indicate that MSTES has potential as effective thermal storage in support of flexibility and low cost low carbon heat in both HP and CHP based DH systems.

ACKNOWLEDGEMENTS

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