Whole-system value of electrified district heating networks in decarbonising heat sector in the UK

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Abstract

The UK's heat sector predominantly relies on natural gas and is responsible for about one-third of overall carbon emissions. Heating in domestic and commercial buildings contributes to about 20% of annual carbon emissions. Although the heat sector is one of the most challenging to decarbonise, electrifying the heat delivery in domestic and commercial buildings could significantly reduce carbon emissions in line with the UK Government's climate targets. This transition could also deliver significant reductions in overall energy system costs due to higher cross-vector flexibility in the electricity and heat sectors enabled by centralised and decentralised electric heating with thermal energy storage. While implementing electrified district heating networks will be prone to geographic limitations, centralised electric heating may potentially save significant costs due to efficiency benefits compared to decentralised solutions. The aim of this paper is to assess the whole-system value of using centralised heating technologies, including heat pumps, electric boilers, and thermal storage, to supply a proportion of heat demand in the UK in 2035, in contrast to decentralised electrified heat supply. The results of quantitative modelling presented in the paper demonstrate that using centralised electric heating can lead to significant annual system cost savings when compared to a decentralised electric heating paradigm.

1 Introduction

In 2019, the UK became the first major economy to pass legislation aimed at bringing carbon emissions to net zero by 2050 [1]. Currently, a third of carbon emissions in the UK are associated with the heat sector [2], [3], [4], while another third is generated in the transport sector [5]. Decarbonisation scenarios for the energy system envisage replacing fossil fuels with low-carbon and zero-carbon energy carriers (e.g., electricity and hydrogen [6]) produced from renewables or other zero-carbon sources. Based on the UK Government's Net Zero Strategy, by 2030 all new cars will be zero-carbon (e.g., electric or hydrogen vehicles) and all new appliances for space and water heating in domestic and commercial sectors will have to be low-carbon/zero-carbon (e.g., heat pumps and hydrogen boilers) by 2035 [7]. Furthermore, the Strategy envisages a complete decarbonisation of the electricity sector by 2035, supporting the decarbonisation of other energy sectors through electrification of heat and transport sectors. However, rapid expansion of renewable resources and their integration into the electricity sector will require significantly increased volumes of flexible assets in the energy system that would not only ensure adequacy and security of energy supply but also reduce the overall system costs through increasing the utilisation levels of different energy system assets. Therefore, a coordinated approach is needed to ensure maximum utilisation of cross-vector flexibility and minimise the overall cost of transition to net-zero carbon energy system in the UK.

There is a variety of flexible solutions that can reduce the cost of investing into and operating future multi-vector energy systems. Examples include Demand-Side Response (DSR), Electrical Energy Storage (EES), Thermal Energy Storage (TES), reinforcement and expansion of interconnectors, expansion of low-carbon/zero-carbon flexible generators, as well as power-to-gas and gas-to-power technologies as cross-vector flexibility resources [8–10]. Utilisation of large-size centralised and small-size decentralised assets, including flexibility sources, will have different implications in multi-vector energy systems. Therefore, it is critical to conduct a holistic assessment when quantifying the system cost associated with different decarbonisation scenarios through sufficiently granular modelling of spatial and temporal interactions between energy vectors [11]. One of the main benefit of cross-vector flexibility is expected to materialise through reduced peak demand in different energy subsectors, which could translate into billions of pounds in annual cost savings. More specifically, cost savings in the electricity sector delivered through deployment of flexibility and sector coupling would include a range of cost categories, including: (1) reduced investment costs of low-carbon and zero-carbon generation capacity, (2) reduced reinforcement costs of the transmission/distribution network, (3) reduced investment costs of interconnection capacity, and (4) reduced operation costs.

Previous research on the integration of different energy sectors [9–13] demonstrated that implementing Smart Local Energy Systems (SLES) with integrated local heat and electricity networks can deliver a net-zero emission energy system at a lower overall cost with a substantial benefit in deferring and reducing system capacity expansion and disruptions [14].

This indicates that rolling out Electrical District Heating Networks (E-DHNs) to supply a proportion of the annual heat demand in the UK could potentially reduce the overall system costs as it transitions towards net-zero carbon. In this paper, a whole-system analysis is carried out using the Whole-electricity System Investment Model (WeSIM) to evaluate the potential cost savings from rolling out E-DHNs to supply some of the UK's annual heat demand in 2035, by quantifying system cost reduction compared to relevant counterfactual scenarios.

2 Methods and Assumptions

Future low-carbon and zero-carbon electricity grids will include a significant volume of flexible technologies with temporal coupling constraints, such as ESS and DSR, requiring accurate characterisation of temporal interactions across different time scales and asset types. Utilisation of various small-scale and large-scale flexible technologies can reduce both long-term investment costs as well as short-term operation costs. Therefore, it is critical to design a single model that includes these features and is able to capture the trade-offs between a variety of flexible assets. WeSIM as a holistic system analysis model has been developed at Imperial College London to simultaneously optimise long-term investment decisions against short-term operation decisions, across generation, transmission, distribution, and storage facilities in a unified form. The detailed mathematical formulation of WeSIM is introduced in [15] and the model has been implemented in FICO Xpress [16]. The structure of WeSIM is outlined in Fig. 1.

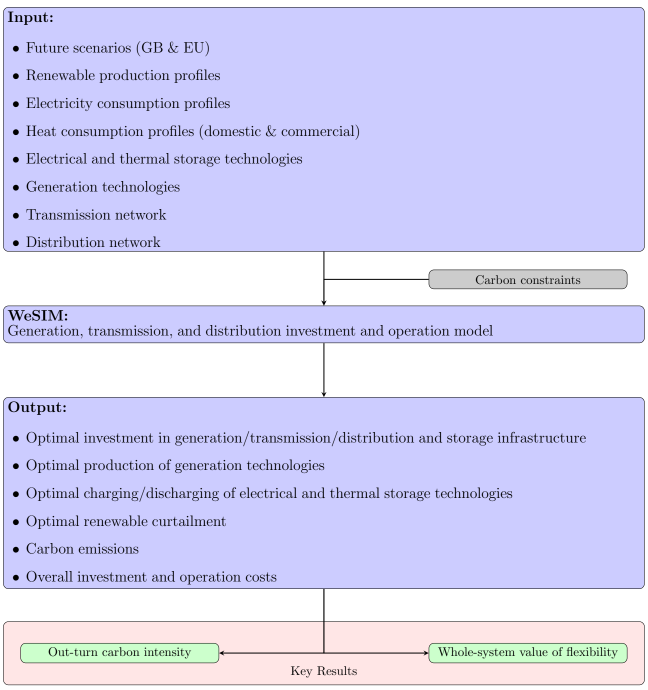

Fig. 1: The outline of the WeSIM model.

WeSIM determines the optimal location and capacity for investment into generation, network, and storage infrastructure to supply the forecasted electricity demand at minimum cost under relevant adequacy and security constraints, including Loss of Load Expectation (LOLE) and rate-of-change of frequency (RoCoF). The main distinctive feature of WeSIM compared to other models is its capability to simultaneously optimise investment and operation decisions, allowing it to identify cost-optimal trade-offs between using flexible resources, such as ESS and DSR, and conventional reinforcements. Furthermore, an approach based on statistically representative networks is used in WeSIM to quantify the reinforcement cost of distribution networks [17]. In addition, WeSIM can evaluate carbon emissions of different generation technologies and optimise the investment and operation decisions while meeting a given carbon intensity target, including net-zero carbon emissions.

WeSIM solves a single large-scale optimisation problem to find the least-cost investment and operation decisions within two different time scales: (1) the long-term period for investment decisions within typically a single year, and (2) the short-term period for operation decisions within typically hourly or half-hourly intervals. In other words, the optimal solution of the WeSIM model determines the least-cost investment decisions within a single year and operation decisions within 8,760 hours of the year to supply the forecasted electricity demand. The main characteristics of the WeSIM model include: (1) DSR capability, (2) supply-demand balance, (3) carbon emission constraints, (4) generator operating constraints, (5) ESS and TES balance and operating limits, (6) constraints on electricity imports/exports, (7) transmission/distribution network investment/reinforcement, (8) reserve/response constraints, and (9) system adequacy/security constraints.

In this study, WeSIM is extended to evaluate the whole-system implications of rolling out E-DHN at the UK level. Various electrified heating technologies considered in the extended version of the WeSIM model include:

- Centralised Electric Boilers (C-EB),
- Centralised Air-Source Heat Pumps (C-ASHP),
- Decentralised Air-Source Heat Pumps (D-ASHP).

Also, it is assumed that decentralised and centralised heating technologies are equipped with Decentralised TES (D-TES) and Centralised TES (C-TES), respectively. In this study, E-DHN consists of C-EBs and C-ASHPs with C-TES. However, D-ASHPs with or without D-TES are also included in WeSIM to evaluate the whole-system value of centralised electrified heating scenarios compared to decentralised electrified heating.

In WeSIM, the GB network is represented with five main regions, as illustrated in Fig. 2, including: 1) Scotland, 2) North England and Wales (EW-N), 3) Middle England and Wales (EW-M), 4) South England and Wales (EW-S), and 5) London. In each region a distinction is made between urban, sub-urban and rural areas. For this study, it is assumed that a net-zero emission electricity sector supplies the electrified heating technologies in 2035 as target planning year. It is assumed that only 50% of the total domestic and commercial heat demand in the UK (632 TWh) is supplied by electrified heating technologies. Furthermore, three days with extreme weather conditions are assumed in order to ensure adequate infrastructure capacity even in the case of a 1-in-20 cold winter. Finally, levelised cost assumptions for different low-carbon generation technologies are presented in Table 1. The assumed investment cost of battery storage is £187.5/kWh.

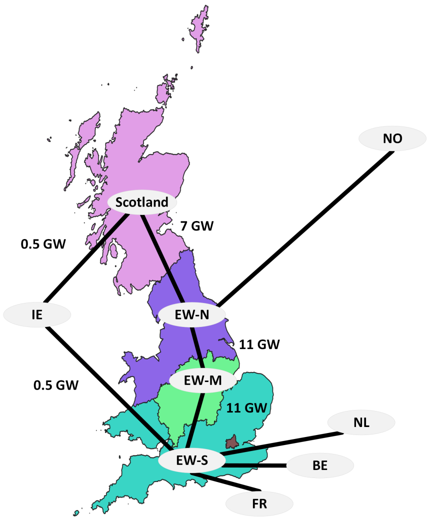

Fig. 2: The topology of the GB network with interconnections.

Table 1 Cost parameters of different generation technologies.

Technology	LCOE (£/MWh)
Nuclear	92.5
Wind (offshore)	35.0
Wind (onshore)	50.0
Solar	50.0

3 Results and Discussion

In this section, three counterfactual scenarios are considered to assess the system implications of rolling out E-DHN at the UK level. For all counterfactual scenarios, it is assumed that 100% of the electrified heat demand is supplied by D-ASHP under different uptake levels for D-TES as summarised below:

1. **Counterfactual Scenario 1 (uptake level of D-TES = 0%):** There is no D-ASHP equipped with D-TES.
2. **Counterfactual Scenario 2 (uptake level of D-TES = 20%):** 20% of D-ASHPs are equipped with D-TES.
3. **Counterfactual Scenario 3 (uptake level of D-TES = 40%):** 40% of D-ASHPs are equipped with D-TES.

Furthermore, three sets of scenarios are considered in order to evaluate different uptake levels of E-DHNs in supplying the electrified heat demand at the UK level, wherein E-DHNs may either *include* or *exclude* C-EBs in addition to C-ASHPs. These scenarios are referred to as **Pessimistic**, **Central**, and **Optimistic**. The assumed contribution of E-DHN to supplying electrified UK heat demand across these scenarios is 10%, 20%, and 30%, respectively. Where C-EBs were assumed to be a part of E-DHNs, the assumption was that the installed capacity of C-ASHPs was sufficient to meet 50% of peak heat demand supplied by E-DHNs, while in case where E-DHNs did not include C-EBs, the size of C-ASHPs was assumed sufficient to cover the peak heat demand on their own.

Each set of Pessimistic, Central, and Optimistic scenarios is superimposed on the three counterfactual scenarios including:

- **Category 1 (D-TES = 0%)** – There is no D-ASHP equipped with D-TES where all C-ASHPs are equipped with C-TES.
- **Category 2 (D-TEP = 20%)** – 20% of D-ASHPs are equipped with D-TES where all C-ASHPs are equipped with C-TES.
- **Category 3 (D-TEP = 40%)** – 40% of D-ASHPs are equipped with D-TES where all C-ASHPs are equipped with C-TES.

In addition to the uptake scenarios described above, the whole-system value of E-DHNs will also depend on their Coefficient of Performance (COP), which will be temperature-dependent. Therefore, the sensitivity of the results with respect to low, medium, and high values of COPs is also quantified and the results presented and discussed in the paper.

3.1 Total cost savings vs. counterfactuals

Total system cost savings for Pessimistic, Central, and Optimistic scenarios against the corresponding counterfactuals are depicted in Fig. 3 for E-DHN with C-EBs and in Fig. 4 for E-DHN without C-EBs. Net cost savings relative to counterfactuals are observed in all scenarios, suggesting there is a visible whole-system value of E-DHN with and without C-EBs in terms of reducing the overall system costs at the UK level. The main observations based on the results include:

- For a given counterfactual scenario (i.e., D-TES = 0%, 20% or 40%) the highest cost savings are observed in the cases with high COP, given that higher levels of COP directly result in lower electricity consumption. Conversely, the lowest benefits are found in the low COP cases. This is observed across Pessimistic (left side of Figs. 3 and 4), Central (middle of Figs. 3 and 4), and Optimistic (right side of Figs. 3 and 4) scenarios.
- Cost savings in the cases excluding C-EBs in E-DHN (Fig. 4) are significantly higher than in the corresponding cases including C-EBs in E-DHN (Fig. 3). For instance, the highest cost saving in the Optimistic scenario increases from £0.93bn/yr in Fig. 3 (right) with C-EBs to £1.57bn/yr in Fig. 4 (right) without C-EBs.
- For a given counterfactual scenario and a given COP level, the whole-system benefit increases with higher uptake levels of E-DHN in supplying the electrified heat demand. For instance, in Fig. 3 for D-TES = 20% and medium COP, the total cost savings versus counterfactual increases from £0.16bn/yr in the Pessimistic scenario (left) to £0.31bn/yr in the Central scenario (middle) and £0.46bn/yr in the Optimistic scenario (right).
- Looking at the impact of the counterfactual assumptions, increasing the uptake of decentralised flexibility (i.e., the penetration of D-TES from 0% to 20% and 40%), reduces the benefits of E-DHN with C-TES. For example, in Fig. 3

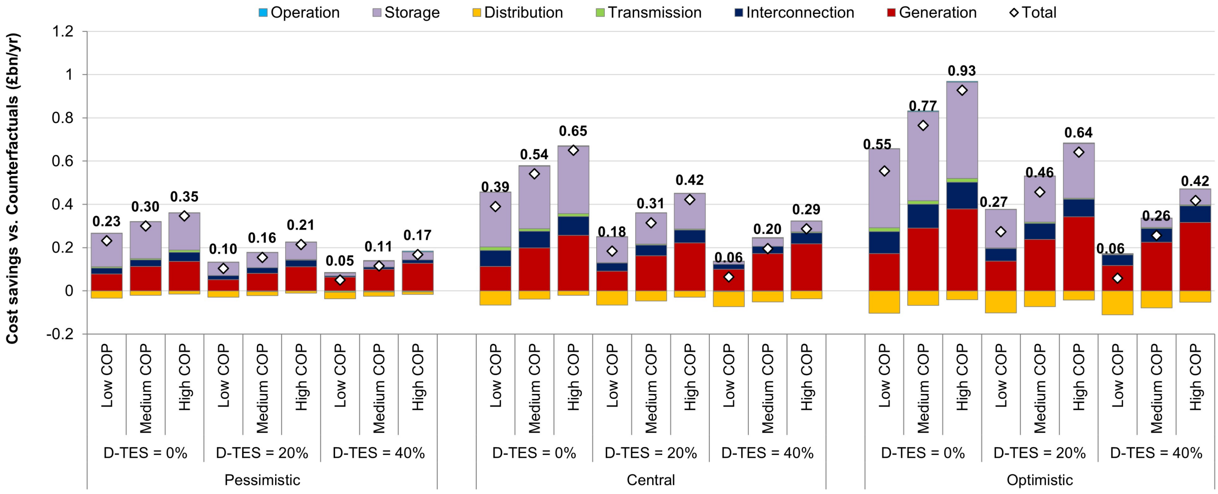

Fig. 3: Total cost saving vs. counterfactual scenarios (with electric boilers).

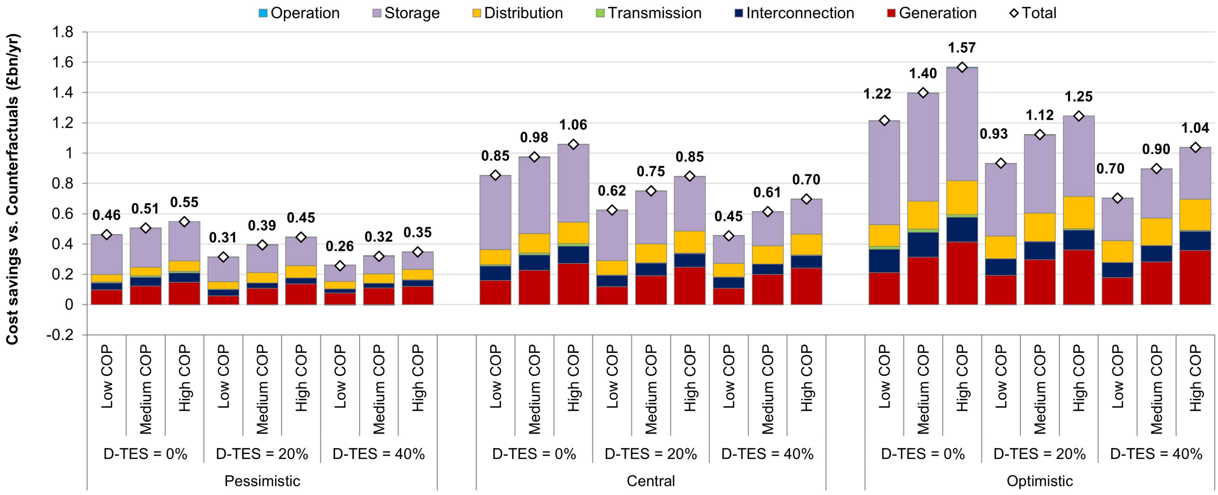

Fig. 4: Total cost saving vs. counterfactual scenarios (without electric boilers).

(middle charts for Central scenarios) with medium COPs, the total cost savings decrease from £0.54bn/yr for D-TES = 0% to £0.31bn/yr for D-TES = 20% and £0.20bn/yr for D-TES = 40%. These results highlight the significant role of D-TES in reducing the system costs associated with integrating electrified heat demand, but also indicate that the whole-system value of E-DHN will depend on the level of flexibility present in the rest of the system.

- For all case studies in Figs. 3 and 4, there is a significant reduction in the total costs of investment into generation, interconnection, and storage facilities. However, in cases including C-EBs in E-DHN (Fig. 3), the reinforcement cost of distribution networks increases as the grid needs to meet a higher peak electricity demand in all scenarios as compared to counterfactual scenarios. This is driven by the utilisation of C-EBs as source of peak heat supply and the fact that their COP is effectively equal to 1. On the other hand, in all cases that did not include C-EBs in E-DHN (Fig. 4), the distribution network reinforcement cost decreases relative to counterfactuals, given that E-DHN only includes more efficient C-ASHPs rather than a mix of C-ASHPs and less efficient C-EBs.

3.2 Total changes in installed capacities vs. counterfactuals

Changes in the total capacity of generation and storage technologies for the Pessimistic, Central, and Optimistic scenarios against the relevant counterfactuals are depicted in Fig. 5 for E-DHN with C-EBs and Fig. 6 for E-DHN without C-EBs. The main observations from Figs. 5 and 6 can be summarised as follows:

- Rolling out E-DHNs can result in a reduction in the total installed capacity of zero-carbon generation and energy storage across all E-DHN uptake scenarios, and particularly for counterfactuals with zero D-TES. Reduction in total installed capacity for the cases excluding C-EBs is significantly higher than for the cases including C-EBs. This follows from the fact that utilising C-ASHPs with high COPs is more efficient than utilising a mix of C-ASHPs and C-EBs with low COPs.
- The volume of capacity displaced through E-DHN increases as the penetration level of E-DHN increases from 10% in the Pessimistic scenarios (left side of Figs. 5 and 6) to 20% in the Central scenarios (middle of Figs. 5 and 6) and 30% in the Optimistic scenarios (right side of Figs. 5 and

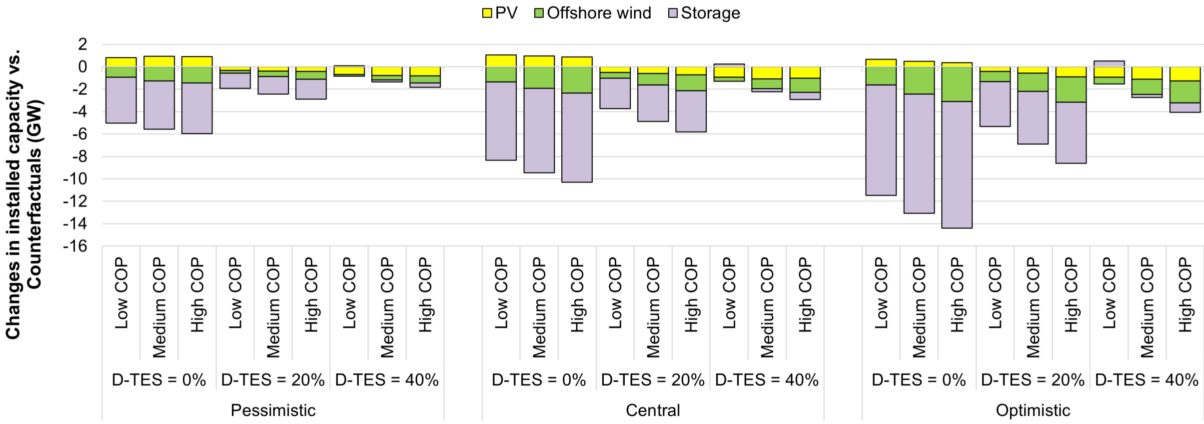

Fig. 5: Changes in installed capacity vs. counterfactual scenarios (with electric boilers).

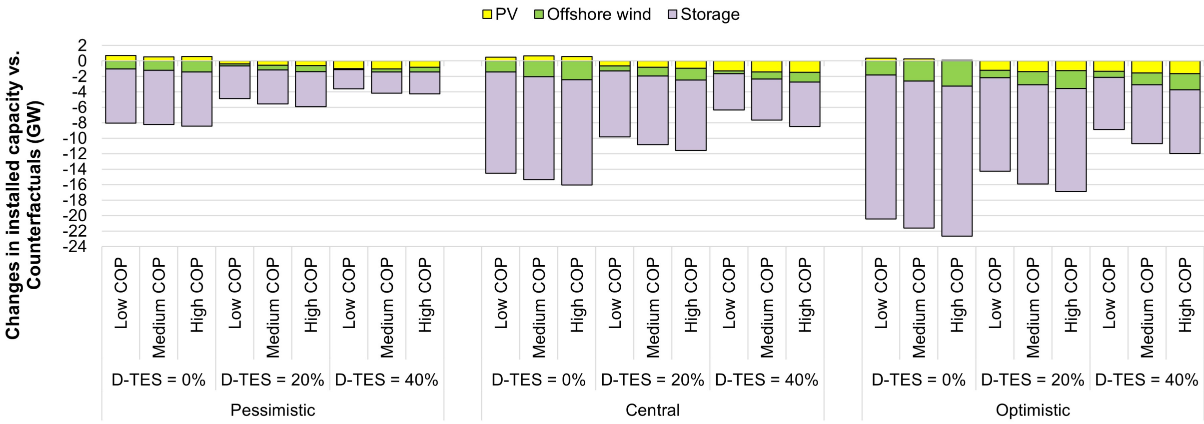

Fig. 6: Changes in installed capacity vs. counterfactual scenarios (without electric boilers).

6). For instance, in Fig. 5 for the zero D-TES counterfactual with C-EBs, the displaced volume of battery storage is observed to be about 4 GW, 7 GW and 11 GW for Pessimistic (left), Central (middle) and Optimistic (right) scenarios, respectively.

- With zero uptake of D-TES in all Pessimistic, Central and Optimistic scenarios, the installed PV capacity slightly increases compared to the counterfactual values. Although this increase never exceeds 1.1 GW. This is driven by a positive correlation between the solar PV generation profile and the heat consumption profile in the commercial sector, so the flexibility unlocked by E-DHN helps to better utilise the PV output at the distribution level and thus save some reinforcement cost.

3.3 Implications for electricity demand for heating

Peak electricity demand is the main driver for the cost of expanding the supply capacity and upgrading the distribution network. Therefore, it is insightful to evaluate the impact of rolling out E-DHNs at the UK level on the total system peak demand. Due to space limitations, only the peak demands for the Central scenarios (either including or excluding C-EBs) and the corresponding counterfactuals are depicted in Fig. 7. Furthermore, the changes in the volume of total electricity demand for the Central scenarios versus counterfactuals are illustrated in Fig. 8. Based on the results reported in Figs. 7 and 8, it can be observed that:

- Total peak demand in the Central scenarios with C-EBs is generally higher than in the corresponding counterfactuals (left side of Fig. 7). On the contrary, the total peak demand in the case without C-EBs is lower than in the counterfactual (right side of Fig. 7). Total annual electricity demand on the other hand is always lower than in the counterfactual. Higher peaks in scenarios with C-EBs are driven by the assumption that E-DHNs utilise C-EBs (with COPs effectively equal to 1) as peak heat supply technologies when C-ASHPs are not able to meet the peak demand on their own, which results in an increase in peak demand compared to a fully decentralised heating scenario. However, the annual utilisation of C-ASHPs (with the higher assumed COPs than D-ASHPs) is significantly higher than C-EBs, which helps to explain the reduction in annual electricity demand in the scenarios with C-EBs versus the counterfactual.
- Within each Central scenario, lower COP values result in higher total peak demands as well as higher total annual electricity demands, and vice versa.
- Increasing the penetration of D-ASHPs equipped with D-TES from 0% to 20% and 40% results in lower peak demand

levels. For instance, in Fig. 7 for Central scenarios with C-EBs under medium COPs, the total peak demand reduces from 153.9 GW for D-TES = 0% to 145.4 GW for D-TES = 20% and 133.5 GW for D-TES = 40%.

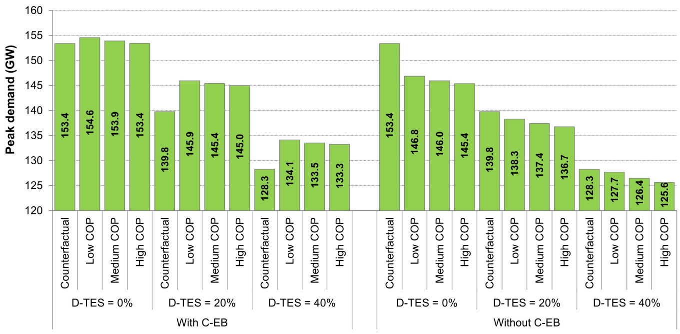

Fig. 7: Reduction in annual peak demand for Central scenarios with/without C-EBs vs. counterfactuals.

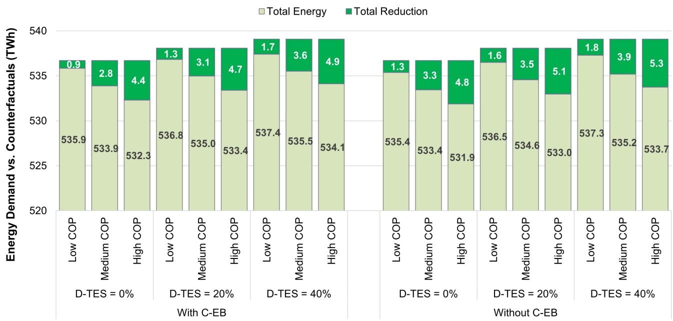

Fig. 8: Reduction in annual energy demand for Central scenarios with/without C-EBs vs. counterfactuals.

4 Conclusions

Quantitative modelling results presented in the paper as obtained from using the WeSIM model indicate that a system-wide roll-out of the E-DHN concept at the UK level could result in significant cost savings from a whole-system perspective. This highlights the potential of the E-DHN concept to deliver whole-system benefits in the electrification of the heat sector. Key observations include:

- Deployment of C-ASHPs to deliver a proportion of electrified heat demand in place of D-ASHPs can potentially reduce the overall system costs, as the COPs of centralised heating technologies can be expected to be higher than for decentralised ones.
- Utilisation of TES can enhance the flexibility of the whole energy system and therefore reduce the overall system costs. Note that this does not include the potential costs and benefits of TES at the end-user side, such as its installation cost or the opportunity to install a smaller ASHP system.
- Scaling up the E-DHN concept with C-EBs could increase system peak demand when compared to counterfactual D-ASHP scenarios. However, the overall energy requirements would decrease due to superior COP values associated with centralised solutions.

Acknowledgements

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