HOUSEHOLD AND WHOLE SYSTEM ASSESSMENTS OF GROUND-SOURCE HEAT PUMP DEPLOYMENT FOR DOMESTIC HEAT DECARBONISATION IN THE UK

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ABSTRACT

Domestic heating accounts for a large share of carbon dioxide emissions in the UK, and only little progress has been made so far in decarbonising the sector. Ground-source energy systems consisting of a ground-source heat pump, a thermal energy store and potentially a backup heating system are an attractive candidate for low-carbon heating of domestic properties. In this work, we combine a household-level ground-source energy system optimisation model with a national whole-energy system optimisation model to perform a holistic assessment of the role and value of ground-source energy systems in the UK net-zero energy system transition. The design and operation of ground-source energy systems is optimised at the household level, and optimal domestic heating technology portfolios and the impact of heat electrification on the wider energy system are assessed using the whole-energy optimisation model. Results show that at the household level larger heat pumps and thermal energy stores that can shift operation to off-peak hours are preferred, while at the whole-energy system level the systems with lowest investment costs are preferred. A combination of investment cost subsidies and/or higher natural gas prices is required for ground-source energy systems to compete with gas boilers. The current subsidy of 7,500 £ requires gas price above 50 £/MWh for ground-source energy systems to become the dominant domestic heating technology, while at subsidies above 10,000 £ ground-source energy systems are competitive at historical average low natural gas prices of 20 to 30 £/MWh.

1 INTRODUCTION

Ground-source heat pumps (GSHPs) are an attractive technology to decarbonise domestic heating, as they are highly efficient and emission-free at the point-of-use. GSHPs are typically combined with thermal energy stores (TES) and optionally backup heaters to form so-called ground-source energy systems (GSESs). Compared to gas boilers however, which are currently the dominant heating technology in the UK and many other countries, GSESs require significantly higher upfront investment costs that are challenging for many households.

To reduce the costs of heat decarbonisation via GSESs, such systems need to be carefully designed and optimised. This optimisation should include not just the system design and sizing, but also the operation. Both electricity prices and the carbon intensity of the electricity vary with time. Therefore, running costs as well as the carbon intensity of heat generation depend on the operation schedule of the GSESs. Additionally, GSESs can be optimised from two different perspectives: households aim to minimise the costs of heating their building, while from a whole-energy system perspective the target is to minimise the overall costs of decarbonisation, including e.g., necessary investments in the power sector. Therefore, the optimal solution for households may differ from the optimal solution for the whole-energy system.

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In this paper, we combine and compare the household perspective and the whole-energy system perspective in the optimisation of design and operation of GSESs. First, GSESs are optimised for selected representative households using a model that optimises component sizing as well as the operation schedule with half-hourly resolution over a typical year. The optimal design and operation for households is identified and analysed. Additionally, a large variety of candidate GSESs, together with associated optimal operation schedules, is created from the household-level optimisation model. These candidates are then provided as options to an integrated national whole-energy system optimisation model, which picks the optimal candidate from the whole-energy system perspective and shows the wider-system impact of the rollout of GSESs. This allows for a comprehensive assessment of the potential role and value of GSESs for domestic heat decarbonisation in the UK.

The idea of using energy from the ground to heat homes has been around for decades, and first prototypes of GSHPs were developed in the 1940s (Manchester, 1947). Since then, the technology has evolved significantly, resulting in two main GSHP designs that differ in the ground heat exchanger (GHE) used. Horizontal GHE systems use horizontal pipes buried at low depth but covering a large area to gather heat from the ground, while vertical GHE systems use boreholes going to depth of 20 to 200 m (Sarbu and Sebarchievici, 2014). In both cases, the heat pump itself uses a conventional vapour-compression cycle to boost the temperature to required levels.

GSHPs have high capital costs compared to other heating technologies. They are also less flexible, i.e., slower to respond to changes in demand than for example gas boilers. Therefore, GSHPs are usually combined with TESs, typically hot water tanks, and backup heaters. TES and backup heater can supply heat during peak hours, allowing the GSHP to be undersized, which can result in lower overall costs (Renaldi *et al.*, 2017). Additionally, the TES can be used to shift electricity consumption away from peak hours, potentially providing large benefits to the whole-energy system (Baeten *et al.*, 2017), as well as electricity cost savings on flexible tariffs for the owner (Olympios *et al.*, 2022).

At a high level, GSESs have at least three degrees of freedom regarding system sizing: the heat pump capacity, the capacity of the backup heater, and the size of the TES. On top of that, the detailed design of each component must be determined, e.g., the design of compressor and heat exchangers or the working fluid. Then, for each potential GSES, the operation schedule must be decided, accounting for e.g., heat demand profiles, variable electricity tariffs, or the marginal grid carbon intensity. Optimisation can be a powerful tool to determine advantageous designs and operation schedules.

Previous studies have addressed parts of this optimisation problem. Dickinson *et al.* (2009) optimised the capacities of a GSHP and a backup gas boiler, as well as the size of the GHE, showing that a hybrid system can reduce costs by 60 % compared to a pure GSHP system, while still significantly reducing emissions compared to gas boilers. TESs were not considered, and no operational optimisation was performed. Alimohammadisagvand *et al.* (2016) focused on the optimisation of the TES for residential heat pump systems, considering different demand response control algorithms. The authors showed that smart control algorithms can reduce costs by up to 10 %. Renaldi *et al.* (2017) developed an integrated framework for the optimisation of design and operation of air-source heat pumps (ASHPs) with TES and electric backup heater, minimising total costs over a 20-year period. The authors modelled heat pump performance as a linear function of ambient temperature, used a synthetic heat demand profile, and accounted for time-variable electricity tariffs. The capacity of the backup heater was not optimised but fixed at 3 kW and 6 kW. The results showed that TESs can significantly reduce the overall costs of the system. Vering *et al.* (2021a) developed a multi-objective optimisation framework to size ASHPs, backup heaters and storage tanks for different user-defined buildings in different locations. The framework uses a detailed model of the heat pump and controller. Parts of the framework were then adapted to combined sizing and operation schedule optimisation frameworks, using a two-stage approach (Vering *et al.*, 2021b) and an integrated approach (Krützfeldt *et al.*, 2021). The authors showed that the optimised systems can achieve cost savings of up to 36 % and emission savings of up to 52 % compared to systems designed following common guidelines (Vering *et al.*, 2021b). The authors then compared different heat pump design

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methods, including one using a dynamic model to optimise heat pumps considering transient behaviour (Vering *et al.*, 2022). The dynamic model was found to increase accuracy, though at higher computational costs. Olympios *et al.* (2022) performed an optimisation of the operation schedule of an ASHP with electric backup heater and different TES systems, using a sophisticated heat pump model that is able to represent off-design performance, as well as a thermal building model. The sizing of components was not optimised. The optimised operation schedule was able to increase the seasonal coefficient of performance (SCOP) and reduce annual operation costs by over 20 % compared to the baseline.

The optimisation studies referenced so far focussed on individual buildings. However, as mentioned above, optimising GSESs from a whole-energy system perspective is another important part of the challenge. Hedegaard and Balyk (2013) performed an optimisation of heat pumps and TESs within a partial equilibrium optimisation model of the Danish energy system considering both investment and operation, with the objective to minimise total system costs. The results showed that TESs and flexible heat pump operation can be valuable to reduce electricity demand peaks. Evins (2015) performed a simultaneous multi-objective optimisation of technology sizing and operation both at the building level and within an energy hub, considering GSHPs and ASHPs among various other technologies. Results showed that GSHPs are especially used in the lowest-emission scenarios. However, the design and sizing of heat pumps was not considered in the optimisation framework. In fact, most whole-energy system optimisation studies that include the heating sector only optimised investments in heating technologies and their operation, but not the technology design. Rinaldi *et al.* (2021) developed an optimisation model that incorporated flexible heat pump operation, but only considered four heat pump types rather than optimising the design. Similarly, our previous work only modelled three heat pump types for residential buildings in our optimisation of decarbonisation pathways for integrated energy systems (Mersch *et al.*, 2023). To the best of our knowledge, only Olympios *et al.* (2024) have attempted to incorporate a large variety of heat pump designs in a whole-energy optimisation model. The authors investigated trade-offs between high-performance and low-cost heat pump designs, considering different compressors, working fluids and heat exchangers. The results showed that high-performance heat pumps can reduce required investments in the power sector. However, low-cost heat pumps may be more economical overall, resulting in lower total system costs and investment requirements for households.

This paper combines a household-level optimisation of the design and operation of heat pumps with an integrated whole-energy system optimisation of net-zero transition pathways. A multitude of heat pump designs are considered in the whole-energy system optimisation. This allows us to investigate design and operation trade-offs both from a household and a whole-energy system perspective. The analysis explores the tension between potentially conflicting objectives of the two perspectives. This represents a significant novelty over existing literature in this space.

The paper is organised as follows: Section 2 introduces the household-level optimisation model and the whole-energy system optimisation model, as well as the methodology to integrate both; Section 3 contains the results and a discussion of our case study of the decarbonisation of domestic heat in the UK; and finally, Section 4 provides concluding remarks.

2 METHODOLOGY

This study uses both a household-level technology optimisation framework and a whole-energy system optimisation model to assess GSHPs from both perspectives. In this section, the two optimisation models are first introduced and then the methodology to integrate both is described.

2.1 Household-level technology optimisation framework

As mentioned above, a GSES is composed of a GSHP pumping heat from the ground via a GHE (here a borehole heat exchanger), combined with a TES (here a stratified water tank) and optionally a backup heater (here an electric resistive heater). The design and operational optimisation of GSESs at the household level is performed in a sequential manner, as illustrated in Figure 1.

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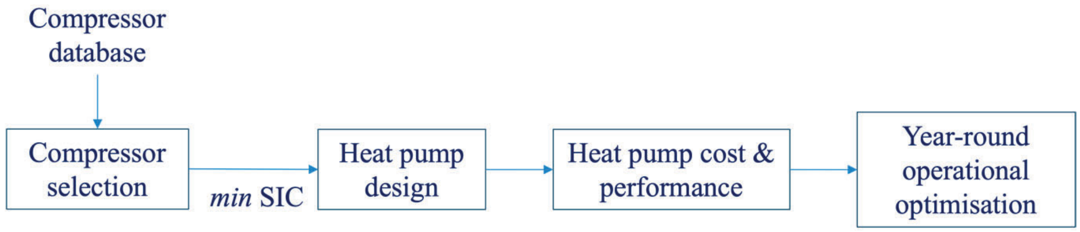

Figure 1: Sequential design and operational optimisation of a ground-source energy system based on a wide database of compressor performance maps obtained from manufacturers and costing models derived from a recent library of price and performance data of domestic and commercial technologies for low-carbon energy systems (Olympios *et al.*, 2021).

First, a compressor unit is selected from a large database of compressor performance maps gathered from different manufacturers for various operating conditions (compressor frequency and suction superheat) and various working fluids. A water-to-water heat pump is then designed (i.e., condenser and evaporators units are sized) to minimise the specific investment cost (SIC) while constraining the coefficient of performance (COP) to be close to the technically achievable maximum, with no subcooling at the condenser outlet. The observed COPs of the optimal heat pumps during the modelled operation are in the range of 2.9 to 3.7. The system is optimised for B0W35 conditions, assuming a 5-K difference in water temperature across the condenser and a 3-K difference in the brine temperature across the evaporator. The compressor off-design performance is explicitly given by the performance maps, while the areas of the brazed-plate heat exchangers are determined using one-dimensional spatially resolved models. Using equal enthalpy-step discretisation, the conjugate convective-conductive heat transfer through the plates is predicted for each node to determine the heat transfer area required to provide the heat flow associated with the specific enthalpy gap, which has been detailed by Sapin *et al.* (2023). Off-design and part-load operating conditions are then explored to determine the heat pump performance for various source temperatures and compressor speeds. Hereby, the fluid-dependent application limits of the compressor unit, as provided by the manufacturer, are respected. This design optimisation method provides a comprehensive link between GSES cost and performance.

Finally, the developed off-design/part-load performance maps for the different GSESs are used to optimise the year-round operation of the GSES for building-specific heat demand profiles and time-varying electricity tariffs. For consistence, in this study a proxy electricity price signal was generated from the heat demand profiles and the non-heat electricity demand profile (see Section 2.3). High-cost electricity is attributed to periods of high heat and electricity demand, typically from 4 pm to 7 pm, while cheaper electricity is available during off-peak hours. The peak and base rates used here, 39.1 p/kWh and 27.9 p/kWh respectively, are based on the UK Flexible Octopus tariffs (Octopus Energy, 2024). To optimise the thermal battery charging schedule, a non-linear programming (NLP) problem is formulated within the open-source Python-based Pyomo framework (Bynum *et al.*, 2021) and solved using the IPOPT (interior point optimiser) NLP solver to minimise the cost of electricity to be paid to meet the demand while respecting the limits and performance of the GSES. Day-ahead operational optimisation is performed throughout the year, to minimise the yearly operational expenditure, and hence the levelised cost of heat (LCOH).

This exercise is repeated for each compressor available in the database with up to 5-kW backup heaters and various water tank sizes. This wide design exploration provides us with a range of configurations for each building (more than 1,000 GSES systems were optimised for the 5 building archetypes considered in this study), the economic values of which are estimated from the end-user perspective, as detailed in Section 3.1, and from the whole-system perspective, as detailed in Section 3.2.

2.2 Whole energy system optimisation model

The Energy System Optimisation (ESO) model is used to assess GSHPs from the whole-energy system perspective. The ESO model was developed by Mersch *et al.* (2023) based on the work of Heuberger

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et al. (2017). It is an integrated energy system optimisation model that identifies cost-optimal transition pathways from 2020 to 2050. ESO uses 5-year time steps to optimise investment and decommissioning decisions, thus solving the capacity-expansion optimisation problem. Simultaneously, for each of the time steps the technology dispatch is optimised with hourly resolution, providing insight into the optimal operation of technologies within the wider energy system. The objective hereby is the minimisation of total system cost (TSC), which is defined as the sum of all investment and operational costs of all technologies from 2020 to 2050, using an interest rate of 3.5 %/a to discount future costs.

The electricity and hydrogen generation sectors as well as domestic, commercial, and industrial heating sectors are explicitly modelled in ESO. Additionally, carbon dioxide removal technologies are modelled. The transportation sector is not explicitly modelled, but additional electricity demand due to the uptake of electric vehicles is considered in line with projections by the Climate Change Committee (2020). As ESO is an integrated energy system optimisation model, any electricity demand from e.g., heat electrification directly translates into an added demand for the electricity sector. Details on considered technologies, as well as the model equations and input data are provided by Mersch *et al.* (2023).

The domestic heating sector is modelled using five archetypal buildings to represent the total UK housing stock. The Cambridge Housing Model (Department for Business Energy & Industrial Strategy, 2015), which is based on data from the English Housing Survey, serves as basis for the housing stock modelling. It contains about 15,000 building archetypes, as well as information on how many buildings of each archetype are present in England. For each archetype, the annual heat demand is estimated using a Standard Assessment Procedure (SAP) methodology. For this study, 5 building archetypes are used. They were determined by applying a *k-medoids* algorithm to the building database. The number of buildings for each archetype is then scaled such that the five archetypes represent the total UK building stock. Details on the buildings are provided in Table 1. Only about 0.2 million new dwellings are built in the UK annually (Office for National Statistics, 2023). Therefore, new-built dwellings are not considered in the model.

Table 1: Key characteristics of the five building archetypes.

	Annual heat demand in 2020	**Number of buildings in UK stock**
Building 1	7,100 kWh	11.3 million
Building 2	11,800 kWh	10 million
Building 3	17,000 kWh	4.7 million
Building 4	26,500 kWh	1.5 million
Building 5	39,100 kWh	0.3 million

To estimate hourly heat demand profile the methodology developed by Watson *et al.* (2019) is applied to generate a relative demand profile. This relative profile is then scaled with the annual heat demand of each building. To be independent of weather anomalies in specific years, the temperature profile from a standard meteorological year is used for the heat demand calculation (European Commission, 2020).

The considered domestic heating technologies in ESO are natural gas boilers, hydrogen boilers, ASHPs, GSHPs, and electric resistive heaters. As mentioned above, so far only a generic small ASHP, a large ASHP, and one GSHP were considered for domestic heating in ESO. In this work, the bespoke GSES designs, determined from the household-level technology optimisation model, are provided as options to the ESO model. District heating solutions are not considered in this work, but investigated in a related analysis (Mersch *et al.*, 2024). Details on the whole-energy system model are provided in Mersch *et al.* (2023) while the integration of the two models is described in the following section.

2.3 Integration of household-level and whole-energy system optimisation models

The household-level and whole-energy system optimisation models are integrated as shown in Figure 2. To ensure consistency in the model integration, first two sets of data are transferred from ESO to the

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household-level optimisation model: the building archetypes and associated heat demand profiles, and the non-heat electricity demand profile. The former serves as direct input to the household-level optimisation model, while the latter is used to generate a proxy electricity price signal, which is then also used as an input to the household-level optimisation.

The proxy electricity price signal ensures that household-level and whole-system level optimisations are aligned. Periods with high electricity demand are identified from ESO, and higher electricity prices are applied during these periods. As the household-level optimisation model seeks to minimise operation costs, the GSHP is operated to avoid these periods of high demand as much as possible, thus shifting demand and supporting the balancing of the wider energy system. The degree to which demand can be shifted depends on the heat pump capacity and TES size.

The household-level optimisation model is then run for each of the five building archetypes, using the proxy electricity price signal and the respective heat demand profile as inputs. The operation of the GSESs is optimised for each configuration, and results are fed back to ESO in form of candidate technologies. Specifically, the capital cost of each GSES configuration as well as the electricity consumption profile are provided as input data to ESO. Finally, a whole-energy system optimisation is performed in ESO to assess the competitiveness of the different GSES configurations. This allows for the comparison (i) between different GSES configurations; and (ii) between GSESs and alternative heating technologies from the whole-energy system perspective.

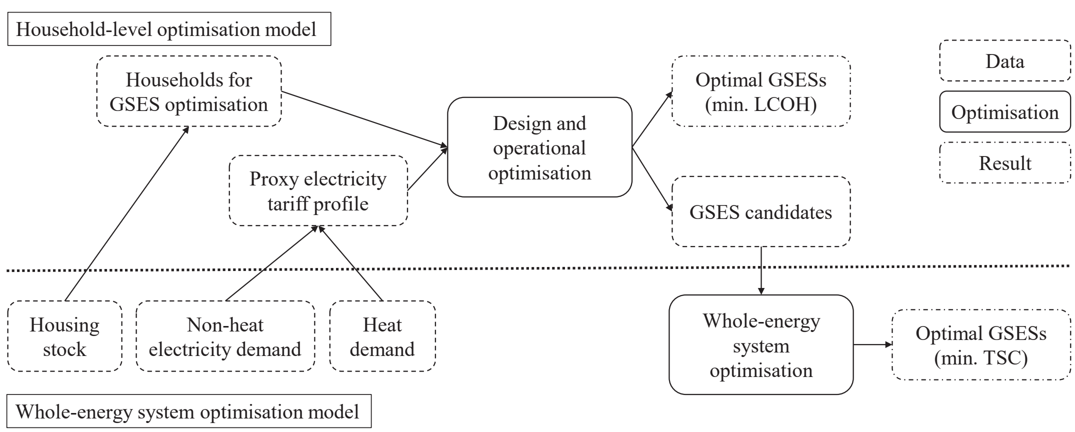

Figure 2: Schematic diagram of the integration of household-level and whole-energy system optimisation models, showing the exchanged data, the optimisations, and the results.

3 RESULTS AND DISCUSSION

3.1 Household perspective: minimisation of heating costs

Households aim to reduce their heating costs and therefore prefer the system with the lowest LCOH. The household-level optimisation model is used to optimise the operation of each GSES that was designed and to calculate the corresponding LCOH (assuming 20-year lifetimes for the heat pump units and 60-year lifetime for the borehole heat exchangers). The resulting LCOH for the five buildings depending on nominal heat pump capacity and TES size are shown in Figure 3. Note that the LCOH also depends on the size of backup heater, and 3-kW and-5 kW electric backup heaters were considered for each heat pump design in addition to standalone heat pumps without backup heater. Figure 3 only shows the results for the backup heater configuration that yields the lowest LCOH for each building. In other words, the backup heater capacity is optimised at each point of the LCOH decision maps.

Figure 3 shows that GSESs with moderately sized heat pumps and TESs result in the lowest LCOH under the assumed component costs and electricity prices. The optimal configuration for Building 1

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from the household perspective consists of a 6.1-kW heat pump with a 5-kWh thermal store and no backup heater. The largest building, Building 5, on the other hand requires a 14.7-kW heat pump with a 30-kWh thermal store and a 5-kW backup heater to achieve the lowest LCOH.

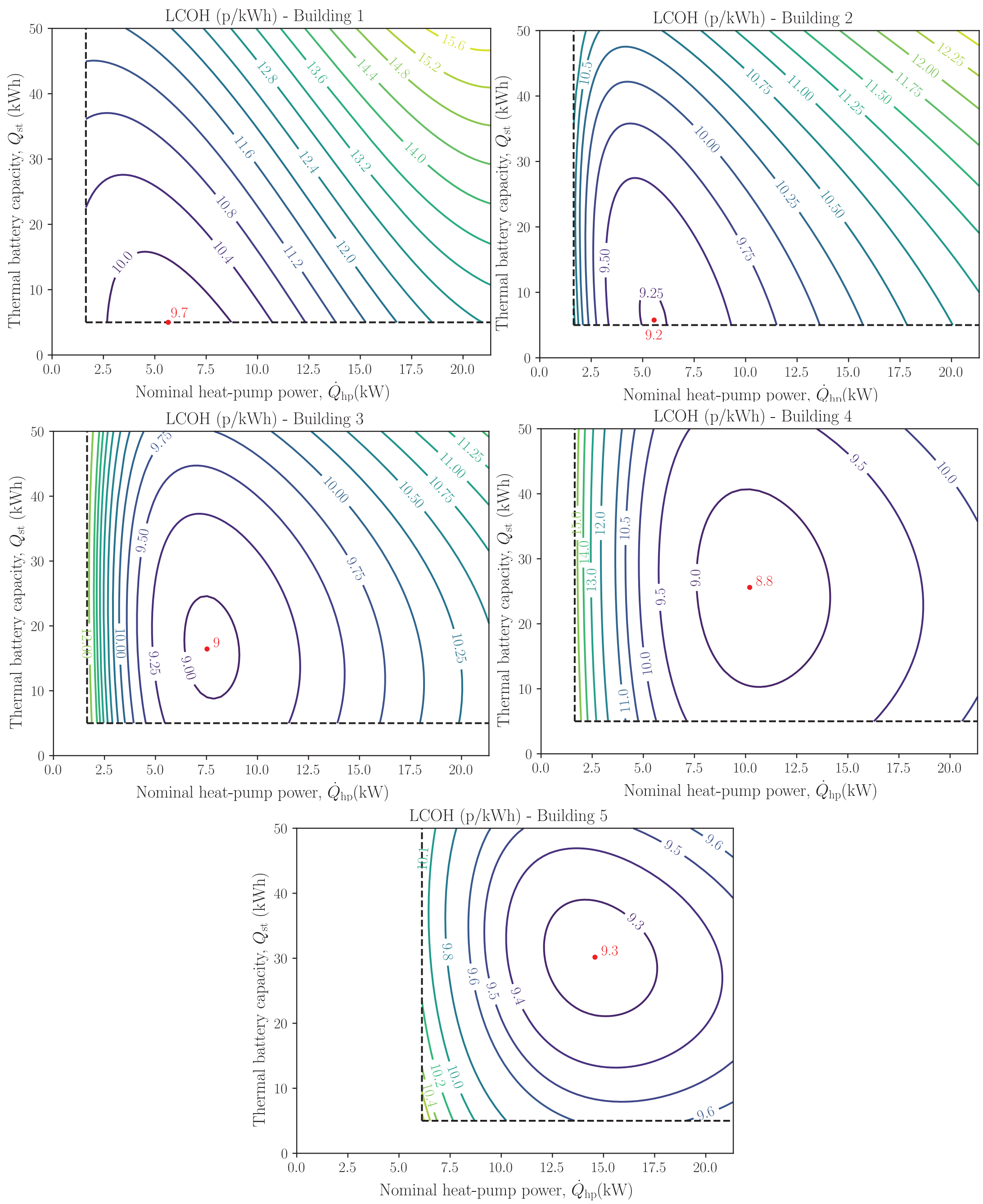

Figure 3: LCOH depending on nominal heat pump power and TES capacity for the 5 buildings. Building 1 is the smallest, and Building 5 is the largest. Only the backup heater configuration resulting in the lowest minimum LCOH is shown for each building. The optimum configuration is highlighted with a red marker. The feasible design space for each building is indicated by the dashed black lines.

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The GSESs achieving the optimal LCOH have higher capital costs than the smallest-possible systems (bottom-left corner in each plot in Figure 3) but can avoid peak electricity prices by utilising the higher heat pump capacity and the TES to shift operation to off-peak hours, thus saving on electricity costs. However, Figure 3 shows that the objective function is relatively flat around the optimum, i.e., small deviations from the optimal component sizes only result in a small increase in LCOH. Only when the GSES is severely undersized and has to operate frequently during peak hours the LCOH increase sharply. Oversizing the heat pump, the TES, or both also increases LCOH, as capital cost increase without any sufficient benefits to operation costs. For example, doubling both the nominal heat pump capacity and the TES capacity of Building 1 leads to about 8 % higher LCOH. It is important to note here that installation and underground heat exchanger costs account for about 40 to 80 % of overall investment costs, thus a doubling of heat pump and TES capacity does not result in a doubling of investment costs. Overall, the results from the household-level optimisation model highlight important trade-offs between investment and operation costs that need to be considered in the design of GSESs.

3.2 Whole-energy system perspective: minimisation of total system costs

At default energy prices, the whole-energy system model prefers smaller GSES for each building compared to the household-level optimisation. For example, for Building 1 the GSES consisting of a 1.6-kW heat pump (in B0W35 conditions with the compressor running at 50 Hz), a 5-kWh TES and no backup heater is primarily deployed, while for Building 5 the preferred GSES uses a 7.9-kW heat pump, a 20-kWh TES and a 3-kW backup heater. It is apparent that any savings in operational costs from the whole-system perspective do not make up for the higher capital costs of larger GSESs. It is important to note however that potentially required electricity transmission and distribution grid upgrades are not included in the model. Therefore, potential savings from reducing peak electricity demand are underestimated. This should be considered in future work.

The results from the whole-energy system model further show that GSESs are not competitive with gas boilers without subsidy at a baseline gas price of 21.2 £/MWh. However, they become economically viable at higher gas prices, or if the investment costs are subsidised. Figure 4 shows the share of domestic heat provided by GSESs in 2050 depending on gas price and subsidy on GSES capital costs. GSES deployment increases with both increasing gas prices and higher subsidies, until finally at high gas prices and/or high subsidies all domestic heat is provided from GSESs. This analysis assumes that GSESs are feasible in every building, which should be refined in future work.

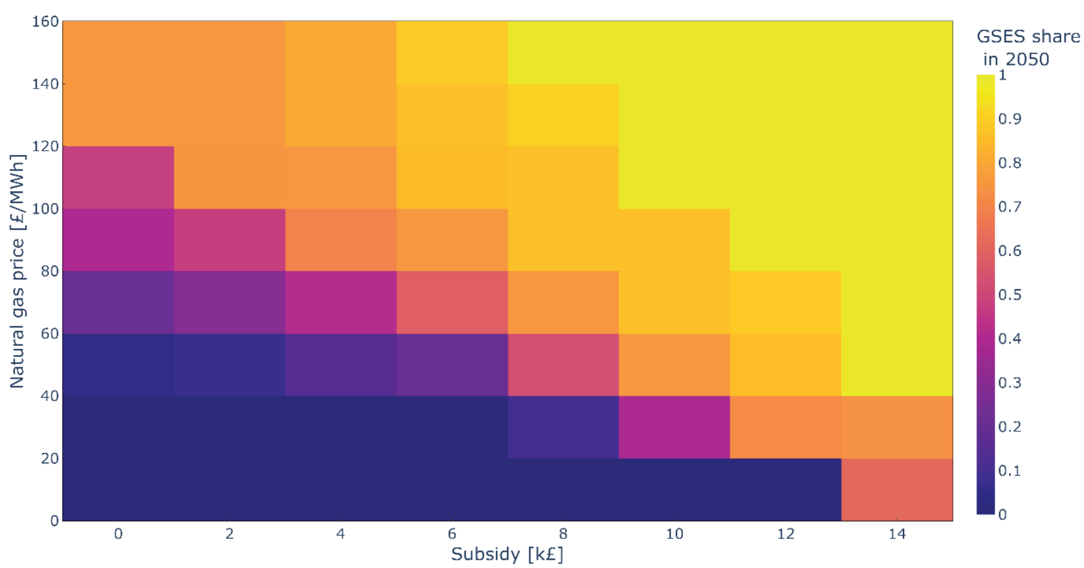

Figure 4: Share of domestic heat provided by GSESs in 2050 depending on natural gas price and subsidy on GSES investment costs.

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The average natural gas price in the UK between June 2017 and June 2021 was 15 £/MWh (Mersch *et al.*, 2023). At this gas price, GSES investment costs have to be subsidised by 14,000 £ for GSESs to become economically viable for some buildings. However, from June 2021 to June 2022, during the peak of the energy crisis, the average gas price in the UK was 72 £/MWh, with daily peaks of 170 £/MWh and higher. At a gas price of 70 £/MWh, a subsidy of 6,000 £ per installation results in about half of domestic heat to be provided from GSESs in 2050, while with a subsidy of 10,000 £ this value increases to over 80 %. The UK government currently offers a subsidy of 7,500 £ per heat pump installation under the so-called Boiler Upgrade Scheme. At this subsidy level, a gas price of 50 £/MWh results in 50 % GSES deployment, while for gas prices of 90 £/MWh and higher over 80 % of domestic heat is supplied from GSESs.

It is important to note here again that this analysis only considers GSHPs. ASHPs, which offer lower investment costs but have a lesser performance, were removed from the whole-energy system model, but will be included in future work. The fact that the GSESs with the lowest investment costs are preferred suggests that the cheaper ASHPs can be a cost-competitive alternative.

High uptake of GSESs, together with the deployment of electric vehicles, results in about a doubling of annual electricity demand. Figure 5 shows how the demand is met while the power sector is being decarbonised. In 2050, most electricity is generated from zero-carbon sources. Nuclear power and wind each provide about a third of the total generation. Solar PV generates the third-most electricity in 2050 (about 13 % of the total), while bioenergy and imports via interconnectors also contribute. Open-cycle gas turbines (OCGTs) and combined-cycle gas turbines (CCGTs) provide important peak power generation capacity, but only generate a fraction of the annual electricity demand. Their emissions are offset by bioenergy with carbon capture and storage (BECCS) to achieve net-zero emissions overall. Currently no BECCS capacity is installed in the UK, but plans are underway to convert an existing 2.6 GW bioenergy plant. The results show that the power sector can provide the low-carbon energy required to decarbonise the domestic heating sector with GSESs.

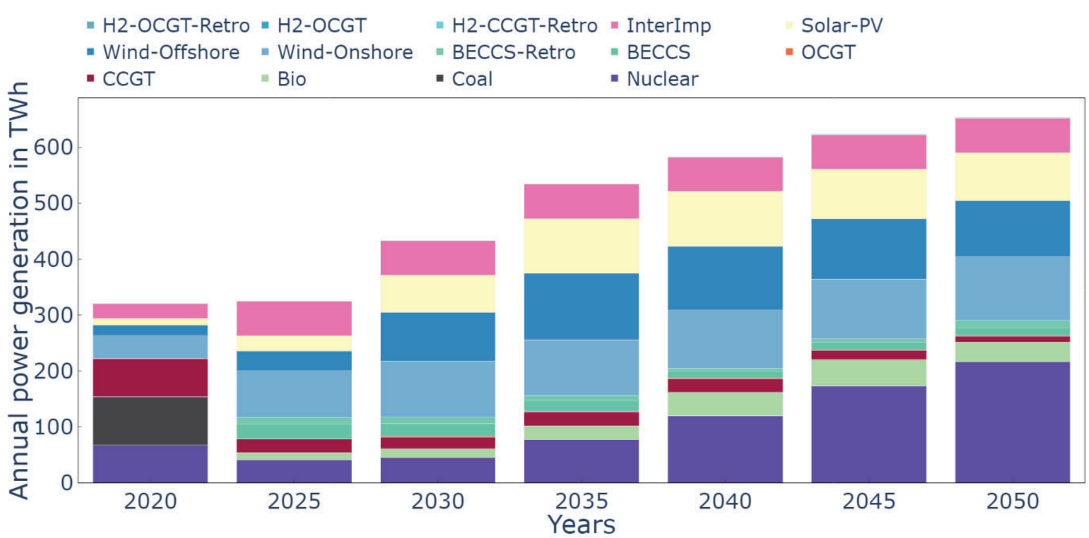

Figure 5: Evolution of the annual electricity generation from 2020 to 2050 in the scenario with a natural gas price of 50 £/MWh and a subsidy of 14,000 £ for GSES installations. OCGT stands for open-cycle gas turbine, CCGT for combined-cycle gas turbine, BECCS for bioenergy with carbon capture and storage, InterImp for interconnections, and Retro indicates retrofits.

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3.3 Discussion

The discrepancy between the optimal GSESs from the household perspective (larger GSHP, larger TES) and whole-energy system perspective (smaller GSHP, smaller TES) can potentially be explained by two hypotheses: (i) the household-level optimisation model overestimates operation cost savings from demand shifting; and (ii) the whole-energy system model underestimates cost savings from reductions in peak electricity demand. The first hypothesis suggests that the difference in peak and off-peak household electricity prices does not accurately reflect the difference in actual marginal electricity generation costs in the whole-energy system. A more dynamic pricing approach rather than fixed peak and off-peak times with predetermined tariffs could help to provide more accurate demand-shifting incentives. The second hypothesis suggests that the costs of potentially required network reinforcements due to higher electricity demands are significant. The whole-energy system model so far only considers the impact on required generation capacity as well as operating costs of generators, but grid reinforcements are not yet included.

The whole-energy system model results suggest that subsidies are required for GSESs to be cost-competitive. However, a share of the required reduction in investment costs can also be achieved by technology cost reductions, e.g., through learning effects, economies of scale, or smarter system layouts. Solutions such as shared ground loops (Shin *et al.*, 2020) or energy tunnels (Ogunleye *et al.*, 2020) have the potential to significantly reduce GHE costs, and communal or district heating solutions may further benefit from economies of scale.

Such shared solutions may provide the additional benefit of centralised thermal stores, addressing another challenge for GSESs: the space requirement of the TES. A 10-kWh TES roughly corresponds to a 220-L water tank, which may prove difficult to fit into some properties and may be unwanted by occupants. Furthermore, communal or district heating systems can enable GSES-based heating for properties without access to the ground, such as flats in densely populated areas.

4 CONCLUSIONS

A household-level optimisation model and a whole-energy optimisation model were used to assess ground-source energy systems (GSESs) to decarbonise domestic heating in the UK. The models were soft-linked by: (i) determining the electricity and heat demand profiles from the whole-energy system model and translating them into a proxy electricity price signal; (ii) performing an optimisation of the GSES operation at the household level to minimise heating costs; and (iii) providing a comprehensive selection of optimised GSESs as domestic heating options to the whole-energy system model. This allowed the assessment of GSESs both from a household and a whole-energy system perspective.

At the household level, moderately sized GSESs result in the lowest levelized cost of heating (LCOH). The optimal systems have a sufficient heat pump capacity and TES size to avoid times of peak electricity tariffs, but not larger. For the smallest building archetypes this corresponds to a 6.1-kW heat pump with a 5-kWh thermal store, while the largest building requires a 14.7-kW heat pump with a 30-kWh thermal store and a 5-kW backup heater. However, the increase in LCOH when deviating from the optimum is moderate, unless the GSES is severely undersized. Doubling both heat pump and TES capacity compared to the optimum leads to an about 8 % increase in LCOH. A large share of the cost is associated with the installation of the GHE. Additionally, higher investment costs are partially offset by lower operating costs, as the larger system can benefit more from off-peak electricity tariffs.

Smaller GSESs with lower investment costs are preferred by the whole-energy system model, suggesting that investment cost savings are more valuable than demand-shifting capabilities. However, costs from required electricity transmission and distribution grid reinforcements were not assessed in the model. The results further show that combinations of high natural gas prices and investment cost subsidies are required for GSESs to be cost-competitive. At the current subsidy level of 7,500 £ per installation in the UK, gas prices of 50 £/MWh and higher are required for more than half of domestic heating in the UK in 2050 to be provided by GSESs. A subsidy of at least 10,000 £ per installations is

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required to make GSESs competitive at historical average low natural gas prices. Further innovation to reduce costs and increase efficiency, as well as community and district heating solutions with shared ground heat collectors can help bridge the gap in costs between gas boilers and GSESs.

NOMENCLATURE

ASHP	Air-source heat pump	(–)
BECCS	Bioenergy with carbon capture and storage	(–)
CCGT	Combined-cycle gas turbine	(–)
COP	Coefficient of performance	(–)
ESO	Energy system optimisation	(–)
GHE	Ground heat exchanger	(–)
GSES	Ground-source energy system	(–)
GSHP	Ground-source heat pump	(–)
LCOH	Levelised cost of heat	(–)
NLP	Non-linear programming	(–)
OCGT	Open-cycle gas turbine	(–)
SCOP	Seasonal coefficient of performance	(–)
SIC	Specific investment costs	(–)
TES	Thermal energy store	(–)

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