net-zero research network

A Network+ for the Decarbonisation of Heating and Cooling

Engineering and Physical Sciences Research Council

FINAL REPORT

NETWORK-H+C
CALL 1 - Heat4All: Economics-informed optimisation model for future equitable decarbonised distributed heating systems

PROJECT DETAILS

Grant number

HC1-01

Award holding organisation

Organisation	University of Surrey

Title of research project

- Heat4All: Economics-informed optimisation model for future equitable decarbonised distributed heating systems

Project details

Investigators

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Grant number

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Final Project Report (up to 10 A4 pages)

1. Introduction

The Sixth Carbon Budget requires a reduction in UK greenhouse gas (GHG) emissions of 78% by 2035 relative to 1990, a 63% reduction from 2019. For the buildings sector, where direct GHG emissions accounts for 17% of UK GHG emissions, the Net-Zero target means to eliminate GHG emissions by 2050. Meanwhile, less than 5% of UK households use renewable heating sources. Decarbonisation of building heating systems is therefore a significant challenge if the UK's 2050 Net-Zero targets are to be reached.

Energy efficiency measures and fuel-switching away from fossil fuels to low-carbon alternatives (e.g., hydrogen and electricity-based heating systems) are considered as two main opportunities for emission reductions. These lower-carbon technologies are likely to be more expensive than current heating systems and as many as 13.4% of households in the UK were classed as fuel poor in 2019. The transition to Net-Zero heating might increase the number of households in fuel poverty due to the inevitable additional costs. Thus, how to minimize fuel poverty in the UK whilst simultaneously delivering Net-Zero targets and develop a future-equitable-decarbonised-distributed (FEDD) heating system is a research question that needs to be answered urgently.

Previously, this problem has been investigated from different angles. In particular, mathematical optimisation models are commonly used in designing and assessing technological solutions to ensure that dynamic heating demands are met at minimum cost. However, a FEDD heating system consists of many components that are closely related to socio-economic development and policy environment. These components are interrelated to each other and present uncertain and dynamic features, associated with spatial heterogeneity.

Therefore, the overarching aim of the research is to develop a practical model to understand how fuel poverty could be minimised in the UK whilst simultaneously delivering upon Net-Zero targets for home heating. The proposed model is designed to be applicable in any community/region, providing a solid framework for future research. The expected outcomes of the model will inform both policy makers and energy suppliers of their decision-making on minimising fuel poverty.

2. Methodology

In this project, a Three-Layer Heat4All modelling approach is proposed to determine optimal technologies and policies to ensure a just energy transition that is realistic and practical. The fuel poverty under a specific policy scenario will be minimised and quantified by combining techno-economic optimisation at both building/household and local energy system scales. With another economy-wide simulation layer, fuel poverty could be further reduced by optimising the policy with reflected macroeconomic performances. The systematic analysis framework involves 5 work packages (WP), as shown in Figure 1. The details of the distributed heating and energy system optimisation model is shown in Appendix 1.1 and the economic and environmental impacts simulation model is explained in Appendix 1.2.

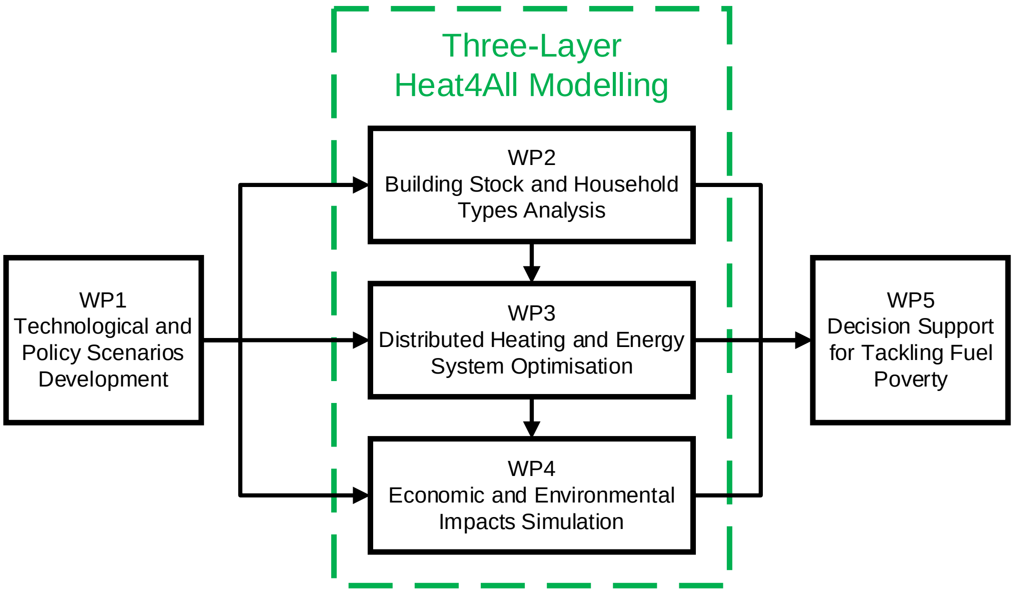


Figure 1: Schematic for Three-Layer Heat4All Modelling

Three policy scenarios are constructed based on these grants. The No Grant (*NG*) omits any form of government contributions. The Business-as-Usual (*BAU*) includes the grants currently applicable to Woking. These include GHG-GJS, ECO and SHDF. The Proposed (*PRO*) additionally includes the PROP grant, an unlimited grant that also funds hot water tanks – a key investment overlooked by existing strategy. The three policy scenarios are summarised in Table 1 below.

Table 1: Policy scenarios description

Identified Attributes	No grant	Business as Usual	Proposed
Policies/grants	No grants	Energy Company Obligation (ECO3)	ECO extension until 2026
		Green Homes Grant (GHG)	Green Homes Grant (GHG)
		Green Jump Surrey (GJS)	Green Jump Surrey (GJS)
		Social Housing Decarbonisation Fund (SHDF)	Social Housing Decarbonisation Fund (SHDF)
			PROP
Heating technologies	New gas boilers	New gas boilers (None)	New gas boilers (None)
	Electric boilers	Electric boilers (GHG)	Electric boilers (GHG, PROP)
	Air source heat pumps	Air source heat pumps (GHG, SHDF)	Air source heat pumps (GHG, SHDF, PROP)
	Hot water tanks		Hot water tanks (PROP)
Efficiency improvements	Loft insulation	Loft insulation (ECO3, GHG, SHDF)	Loft insulation (ECO3, GHG, SHDF, PROP)
	Cavity wall insulation	Cavity wall insulation (ECO3, GHG, SHDF)	Cavity wall insulation (ECO3, GHG, SHDF, PROP)
	Solid wall insulation	Solid wall insulation (ECO3, GHG, SHDF)	Solid wall insulation (ECO3, GHG, SHDF, PROP)
	Double glazing	Double glazing (ECO3, SHDF)	Double glazing (ECO3, SHDF, PROP)

The Baseline scenario considers the heating technologies already installed in the case study area according to the Cambridge Housing Model (CHM). Annual gas and electricity bills are taken by the households with the assumption that the existing heating system keeps operating for the next 20 years. The current carbon intensity of grid (GCI) (i.e., 184.7 gCO_2e/kWh) is used to calculate the GHG emissions from energy system of baseline scenario. When testing other scenarios, the optimisation results provide the plans for heating equipment replacements and insulation measures under a projected GCI. The cost of replacement and installation of boilers, heat pumps, hot water tanks and house insulations are partly covered by grants mentioned above. If the cost exceeds the limit of a certain grant, Woking borough council (WBC) will provide the extra cost.

3. Heating and energy system optimisation

This section discusses the results of the optimal design under three policy scenarios: *NG*, *BAU* and *PRO* with a projected GCI of 15 gCO_2e/kWh (Net-Zero pathways in the Sixth Carbon Budget).

3.1 Optimised solutions under Surrey's 61% emission reduction target

Surrey county has set an minimum 61% emission reduction target across commercial and public buildings by 2035 (surreycc.gov.uk), which serves as a practical start for heating system optimisation.

3.1.1 Insulation plans

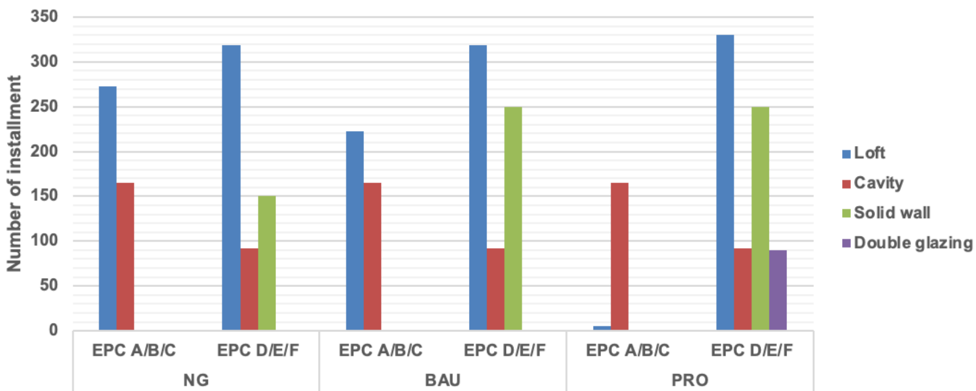


Figure 2: Insulation retrofitting under 61% ER target

Figure 2 displays the insulation plans under different policy scenarios for various EPC rating groups under the constraint of 61% carbon emission reduction from baseline values. In *NG*, a significant increase in retrofitting in EPC A/B/C dwellings occurs, with an additional 268 dwellings installing loft insulation. Furthermore, 150 EPC D/E/F dwellings install solid wall insulation to achieve Surrey's ER target. Under *BAU*, grants are available to EPC D/E/F households. As a result, an additional 100 solid wall insulation measures are installed, and the focus is shifted towards improving the energy performance of the fuel poor dwellings, while some of the GHG mitigation burden is removed from EPC A/B/C dwellings to install loft insulation. This trend continues under *PRO*, where the additional PROP grant provides further funding, especially towards double-glazing.

3.1.2 Heating technology

The results presented in Figure 3 reflect the heating technologies installed to achieve Surrey's 2035 emissions reduction target of 61%. Though gas boilers remain the most prevalent domestic heating technology, retrofitting ASHPs is crucial to decreasing emissions by 61% from baseline values – leading to a 31% increase in total annualised cost for *NG* and *BAU*.

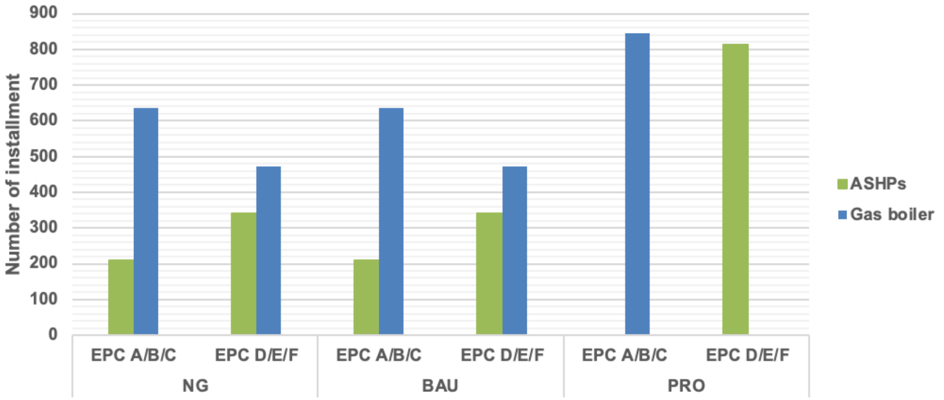
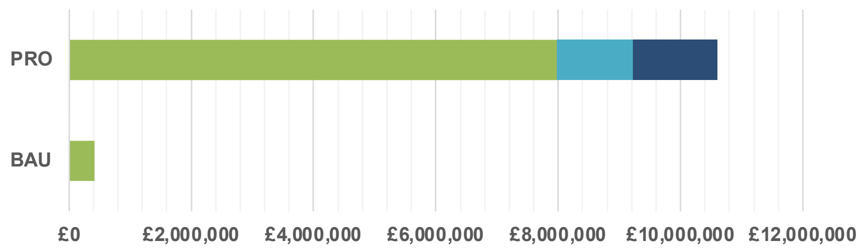


Figure 3: Heating technologies with a 61% ER target

3.1.3 Grant contribution



	BAU	PRO
Electric boilers	£0	£0
ASHPs	£411,600	£7,973,800
Hot water tanks	£0	£1,240,193
Insulation	£0	£1,388,662

Figure 4: Total grant contributions with a 61% ER target

Cost is one of the most significant financial barriers faced in transition to Net-Zero, thus it's important to have an effective and targeted decarbonisation strategy. Figure 4 breaks down the grant contributions under *BAU* and *PRO*. All the grants, except for GHG-GJS, employ a 'fabric first' approach – implying eligible insulation measures must be installed before ASHPs are funded. This promotes the improvement of home energy efficiency, helping to address fuel poverty and thermal discomfort within the homes. However, *BAU* results indicate that the focus must be shifted to renewable heating, such as the installation of ASHPs. Note that the 'fabric first' constraints are not broken here as insulation measures are installed at the relevant dwellings, though not funded by grants. Under *PRO*, since no limit is set on the PROP grant, the overall grant contribution is much higher than the *BAU*. The figure indicates the dominant proportion of ASHPs and smaller contribution to Hot water tanks and Insulation funded.

3.1.4 Energy bills

Fuel poverty is linked to a household's disposable income after energy bills being paid. Hence, decreasing this household energy bill is the key to reducing fuel poverty. Figure 5 outlines the average energy bill for those living in EPC D/E/F homes under various scenarios, including the baseline values. Due to its high unit cost relative to natural gas, electricity consumption dominates the annual expenditure. This is particularly evident when the system is constrained to reducing baseline carbon emissions by 61%, which promotes the use of ASHPs, an electrified form of heating. The significant difference in costs between gas and electricity leads to higher total energy bills – despite the additional insulation. Under *PRO*, the households have unlimited funding to install insulation measures that help reduce the overall energy demand. Despite this increased household energy efficiency, the annual energy bill remains higher than the baseline value. This implies that, without OPEX support, the decarbonisation of heating will lead to higher annual energy bills and can potentially exacerbate fuel poverty. However, this remains energy tariff dependent. More efficient ASHPs and other renewable heating sources that are not trialled in this study may yield contradicting results.

	Baseline	NG	BAU	PRO
Gas	397	£176	£175	£0
Electricity	716	£919	£881	£1,165

Figure 5: Average annual energy bills for EPC D\E\F dwellings per house

3.2 Optimised system designs under different emission reduction targets

To further explore the capacity of the multi-objective optimisation model in achieving Net-Zero targets, the following section discusses effects of various degrees of decarbonisation on the results of optimised heating and energy system design.

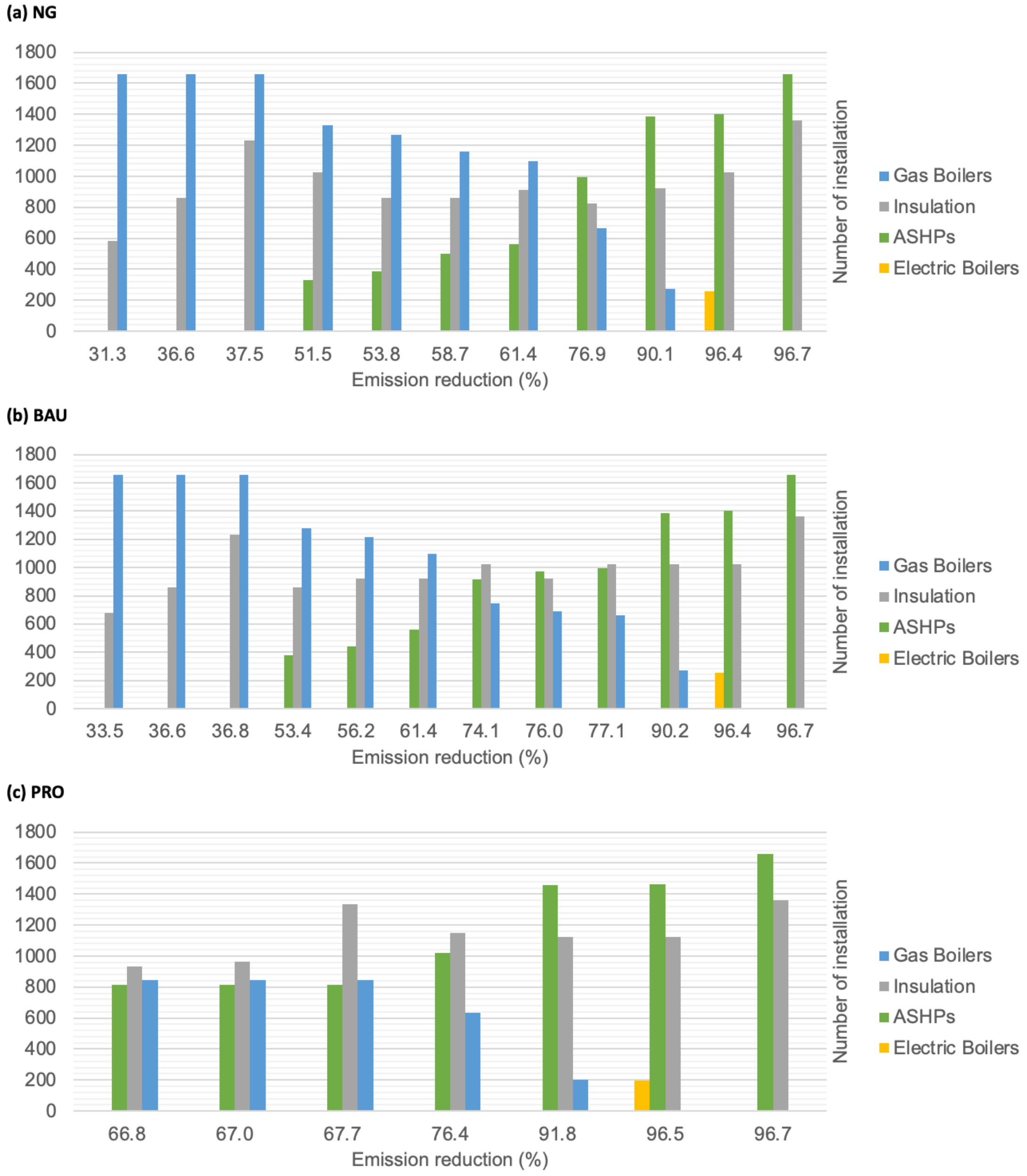


Figure 6: Heating technology results under (a)*NG*, (b)*BAU*, (c) *PRO*

3.2.1 Emission reduction potential

As one of the constraints of optimisation, the emission reduction target (ERT) in the optimisation model only includes the carbon emission of electricity generation and gas consumption. The actual carbon emission reduction from the baseline value achieved in the optimisation model is defined as the carbon emission reduction rate (ER) from 2022 to 2035.

By traversing from 0-100% ER in the optimisation model, we assess how the system design and costs are impacted and identify the maximum possible ER under each scenario. With a projected GCI of 15 gCO_2e/kWh for 2035, the maximum achievable ER is 96.7% comparing with baseline value. The ER potentials under the three policy scenarios are 31.3-96.7% under *NG*, 33.5-96.7% under *BAU*, and 66.8-96.7% under *PRO* respectively.

3.2.2 Technology Changes under different ER

In all cases, a trade-off can be seen between retrofitting insulation measures and ASHPs. The former is cheaper but has a significantly smaller impact on decarbonisation performance of the system. Under *NG*, increasing insulation from 581 to 1234 installations results in a minor increase in emission reductions, reflected by the changes of ER from 31.3% to 37.5% in Figure 6(a). As ERT increases, the system is driven to decarbonise further by installing ASHPs. This tendency results in a compromise between insulation measures and ASHPs, where insulation investment is reduced to facilitate increased ASHPs installation for increased achievement of ER from 37.5% to 51.5%.

Another notable trend from Figure 6 is the phasing out of gas boilers. Under all policy scenarios, the system achieves an ER of more than 90% without fully phasing out gas boilers. This is likely the result of the existing gas boiler options in baseline scenario have lower thermal efficiencies compared to new installations (presented in Appendix 1.1.6 Table 3), so simply replacing the boilers by new boilers would realise emissions reductions. As ERT increases significantly, these gas boilers are replaced by their electric counterparts due to their relatively lower investment cost compared to ASHPs. The dwellings at which these are installed are those with the lowest heating demand. For these households, the operational savings from an ASHP do not outweigh the high associated investment costs. This implies that electric boilers may be a promising solution to the decarbonisation of small homes, provided they are powered by low-carbon electricity. However, if the source of electricity is not fully carbon neutral, the efficient nature of ASHPs makes them the sole solution for minimising carbon emissions, as reflected by the results when ER is 96.7% in all policy scenarios.

4. Whole-economy and environmental impacts simulation

As the choices of heating technologies and insulation measures are affected by ERT and expected GCI for 2035, we further explore the optimal system design and the whole-system impacts under different combinations of ERT and GCI of all policy scenarios.

4.1 Direct GHG emission reduction

Direct Emissions are defined as emissions from sources that are owned or controlled by the reporting entity, which have direct causal linkage with total output of certain categories of industries.

4.1.1 Emission reduction capacity

By traversing from GCI 0-15 gCO_2e/KWh and ERT 0-100%, direct GHG emission reduction capacity of 97 sectors ranges from 65,504 to 71,295 thousand tonnes of CO_2e. For the 3 policy scenarios, more direct GHG emission reduction is achieved as GCI falls, which has more significant impacts than that of ERT. Also, direct GHG emission has an increasing tendency as ERT increases, but some scenarios alleviate the trend. Figure 7 vividly depicts the trends of reduced direct GHG emission under *BAU*, and similar patterns could be observed under *NG* and *PRO*.

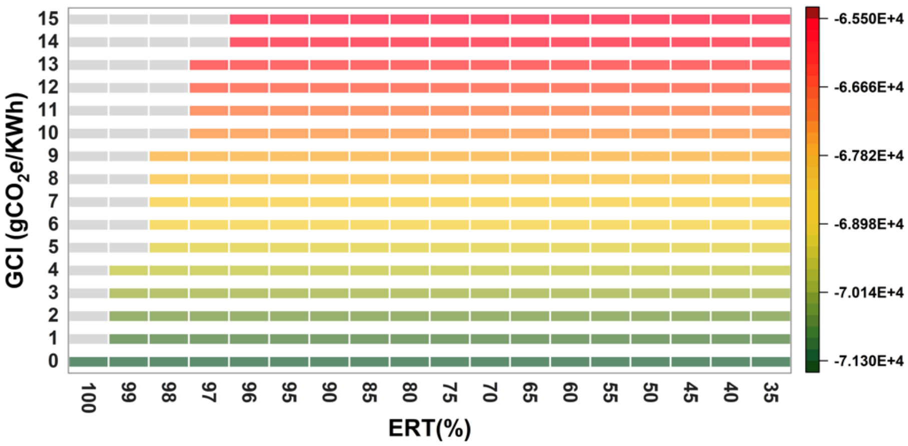


Figure 7: Direct GHG emission reduction under *BAU*
(Unit: mass of air emissions per annum in thousand tonnes of carbon dioxide equivalent)

When comparing the results of the 3 policy scenarios, the results show an inconsistent pattern. When ERT is lower than 80%, more scenarios under *NG* have lower direct GHG emission than *BAU*, especially when ERT is 70%. Direct GHG emission tends to be larger under *PRO* than *BAU* when ER is between 75-95% (Appendix 2 Figure S1(b)). Moreover, when ERT is 85% and GCI is between 1 to 7 gCO_2e/KWh, the results strongly deviate from this pattern. These inconsistencies require further exploration of the contributions of various sectors to GHG emission reduction.

4.1.2 Impacts on different industry sectors

With increased investment in heating equipment and house insulation, total outputs in the whole economy of all combinations of ERT and GCI under 3 policy scenarios increase compared with baseline. For each policy scenario, total output increases as ERT rises, mostly because the total expenditure increases. Here we present typical combinations of ERT and GCI to explain the role of different industries. Figure 8 displays the changes in total output and direct GHG emission by sectors of 3 special combinations. The GCI target for year 2035 is 15 gCO_2e/KWh, and here we explore the direct GHG emission reduction by sectors under target 65% (smallest feasible ERT under *PRO* and closest to Surrey's 61% target) and 96% (largest feasible ERT under all policy scenarios). As we are transitioning to Net-Zero, the combination of ERT 100% and GCI 0 gCO_2e/KWh is also a vital point in revealing the contributions of different industries to direct GHG emission reduction.

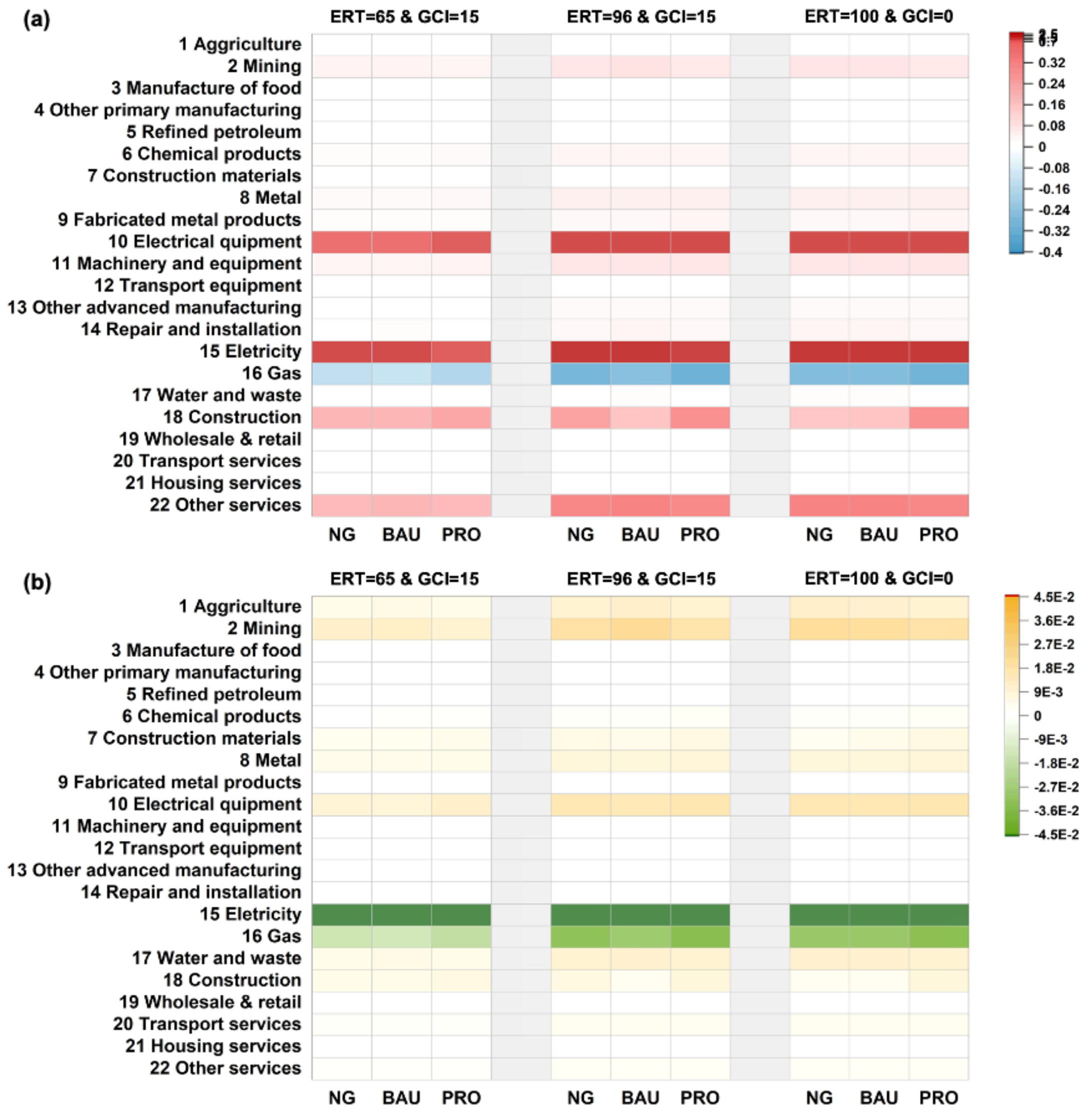


Figure 8: Comparison of (a) changes in total output (Unit: millions £.) and (b) direct GHG emission (Unit: thousand tonnes of CO_2e) by sectors with baseline under policy scenarios *NG*, *BAU* and *PRO*.

Changes in total output by sectors are shown by Figure 8(a), where all the total outputs are increased except for gas industry. The investments in heating and energy system would stimulate the economy with various extents among industries. With less gas boilers, the total output of gas industry decreases as expected. Meanwhile, the direct investment in heating technologies and insulations, as well as changes in gas and electricity bills, brings about stronger increases in electrical equipment, electricity, and construction industry. Ascending total output could also be acquired in fabricated metal products, metal, mining and machinery and equipment industry, as they are vital parts of the supply chain of electrical equipment.

Even though the optimisation plan tries to reduce GHG emission of heating and energy system, the increased total industry outputs further bring about ascending direct GHG emission to the whole economy system. But the increased emissions are greatly hedged by the reduced GHG emission of gas and electricity industry and the overall direct GHG emission still reduce with higher total industry output comparing with the baseline.

4.2 Total GHG emission reduction

Total GHG emission include Scope 1 emissions (direct emissions), Scope 2 emissions from purchased electricity and steam, and Scope 3 emissions from activities from assets not owned or controlled by the reporting organization, but that the organization indirectly impacts in its value chain. Figure S2 in Appendix 2 presents the total GHG emission reduction of *BAU*, and the 3 policy scenarios share the same tendency. Meanwhile, total GHG emission shares the same trends as direct GHG emission for each policy scenario, where total GHG emission has an increasing tendency as ERT increases, more total GHG emission decreases as GCI falls, and the impact of GCI is larger than that of ERT. By traversing from GCI 0-15 gCO_2e/KWh and ERT 0-100%, total GHG emission reduction of 22 industries has a capacity of 65,504 to 82,720 thousand tonnes of CO_2e. When comparing the total GHG emission of the 3 policy scenarios (Appendix 2 Figure S3), certain combinations of GCI and ERT present higher emission than BAU, which resembles that of differences in direct GHG emission between policy scenarios.

As ERT increases, more decarbonisation activities are included in the heat and energy system, leading to a higher cost for heating technology replacement and insulation measures. The higher cost further increases the total industry output of whole economy system, resulting in higher total GHG emission. However, the GHG emission reductions from the heating and energy system significantly outweighs the increased total GHG emission of whole economy system and that is why total GHG emission is still reduced compared with baseline.

5. Optimised FEDD heating system for tackling fuel poverty

The total GHG emission differences among scenarios are all smaller than 100 tonnes of CO_2e but come with various system optimisation plans and different costs. To secure the optimal solutions for tackling fuel poverty, we further investigate the cost-effectiveness of GHG emission reduction.

5.1 Total GHG emission reduction cost

Figure 9(a) displays the total GHG emission reduction cost per thousand tonnes of CO_2e under *BAU*. Similar patterns could be observed under *NG* and *PRO*. As ERT decreases, the unit GHG emission reduction cost keeps falling with an accelerated decreasing rate. For GCI, the unit GHG emission reduction cost descends more evenly.

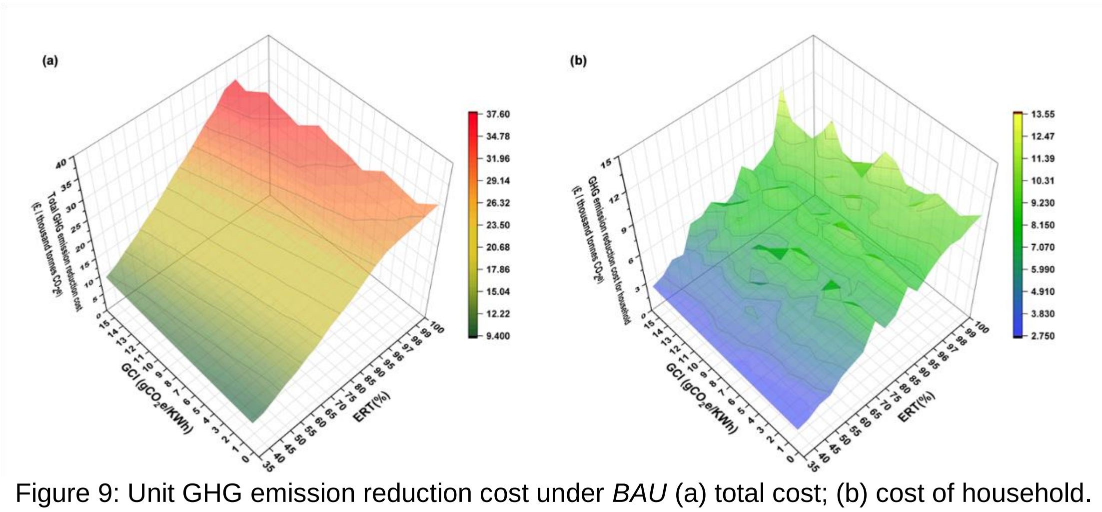


Figure 9: Unit GHG emission reduction cost under *BAU* (a) total cost; (b) cost of household. (Unit: £/ thousand tonnes of CO_2e).

Figure 10 presents the differences of unit GHG emission reduction cost between policy scenarios. Variances of the differences could be observed when comparing *NG* and *BAU*, while the unit cost of GHG emission reduction under *PRO* are all higher than those of *BAU* under the same GCI and ERT. The unit cost gap between *NG* and *BAU* ranges from £ -0.3 to £ 0.4, while the pattern is not clear. However, for the unit cost gap between *PRO* and *BAU*, there's a decreasing trend as ERT increases from 65 to 100% for all GCIs.

5.2 GHG emission reduction cost of household

Figure 9(b) presents the household cost for per thousand tonnes of CO_2e under *BAU*. The unit GHG emission reduction cost for household demonstrates an increasing trend as ERT climbing up. Also, like the unit total cost, the unit household cost descends more evenly as GCI decreases. Figure 11 displays differences of unit household cost for GHG emission reduction between policy scenarios. Similar patterns could be overserved from differences in direct GHG emission reduction and total GHG emission reduction. Comparing *NG* and *BAU*, when ERT is lower than 80%, less insulation measures are adopted under *NG* for most combinations, which leads to a lower cost. While when ERT is 55% and GCI is lower than 7 gCO_2e/KWh, more insulation measures are installed, which probably causes the increase in household cost. When comparing *PRO* and *BAU*, *PRO* provides lower unit household cost in most combinations of GCI and ERT, especially when GCI is lower than 10 gCO_2e/KWh. When ERT is lower than 90% and GCI is higher than 10 gCO_2e/KWh, more insulation measures and more electric boilers are adopted for system optimisation under *PRO*, but the interactions of technologies are still complicated in influencing the final cost.

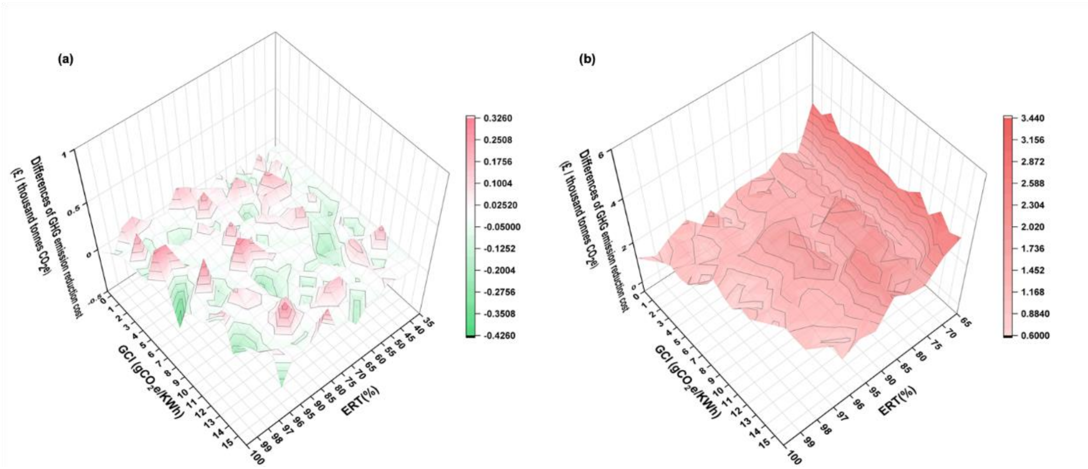


Figure 10: Comparison of unit GHG emission reduction total cost (£/ thousand tonnes of CO_2e). (a) *NG* vs *BAU*; (b)*PRO* vs *BAU*. Positive number means the former is higher than the latter.

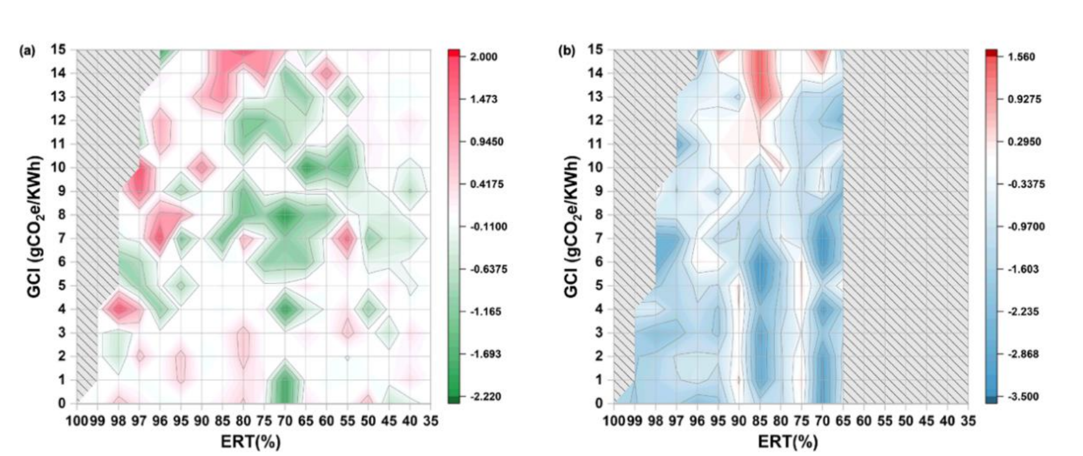


Figure 11: Comparison of unit GHG emission reduction cost of household (£/ thousand tonnes of CO_2e). (a) *NG* vs *BAU*; (b)*PRO* vs *BAU*. Positive number means the former is higher than the latter.

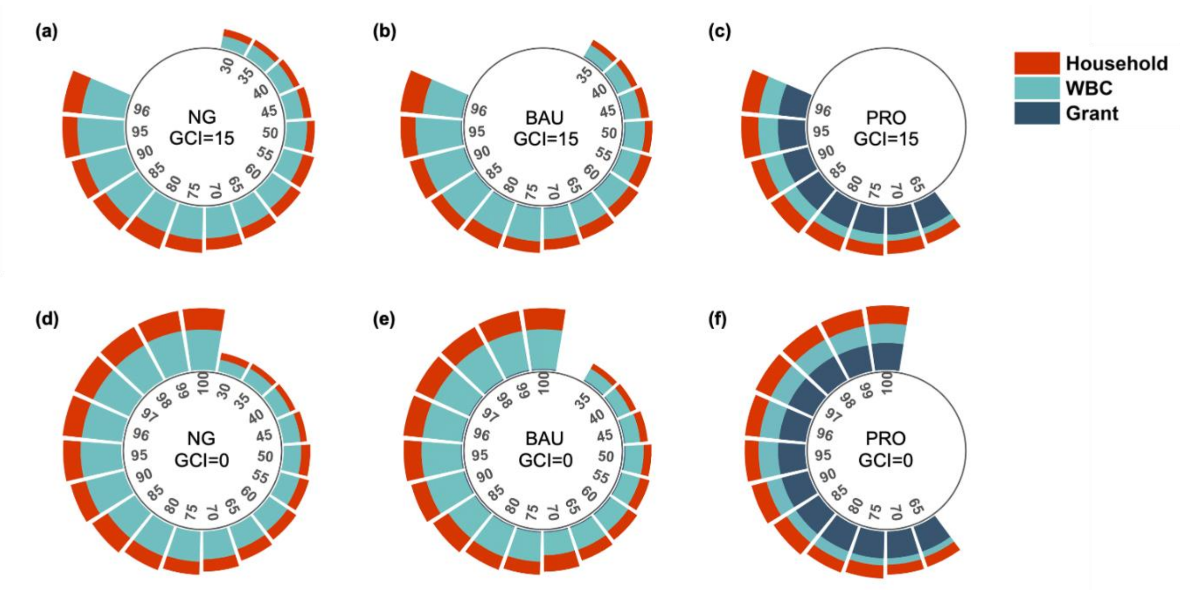


Figure12: Shifts of annualised cost among household, local authority, and grant under different scenarios (Unit: £). ERT is indicated by the circularly arranged numbers.

5.3 Cost shift among stakeholders

Given that the total annualised cost decreases as GCI decreases, Figure 12 displays changes of total annualised cost as ERT increases when GCI is 0 gCO_2e/KWh (a-c) and 15 gCO_2e/KWh (d-f), which are the lowest and the highest annualised cost respectively. For all the 3 policy scenarios, total annualised cost has an increasing tendency as ERT increases, and annualised costs of household for all housing stock as a total and WBC also demonstrate an ascending trend. Under *NG* and *BAU*, the contribution of WBC is much higher than households. But *PRO* had the least annualised cost for household and WBC under the same GCI and ERT.

The investment in replacement of gas boilers with ASHPs would transfer the demand for natural gas to electricity as the latter had higher energy efficiency and larger GHG emission reduction capacity. Also, insulation of the social housings would reduce the total demand in house heating and thus reduce gas and electricity bills relatively. Under the optimisation target of minimising annualised household cost for social house heating, the burden on household and WBC would be shifted to the PROP grant to tackle fuel poverty for social housings.

5.4 Optimised instalment plans

Considering the analysis above, here we present the optimised plan under various combinations of GCI and ERT. Even though the optimisation target is to solve fuel poverty of social housing, the economic burdens of different stakeholders are also worth taking into consideration.

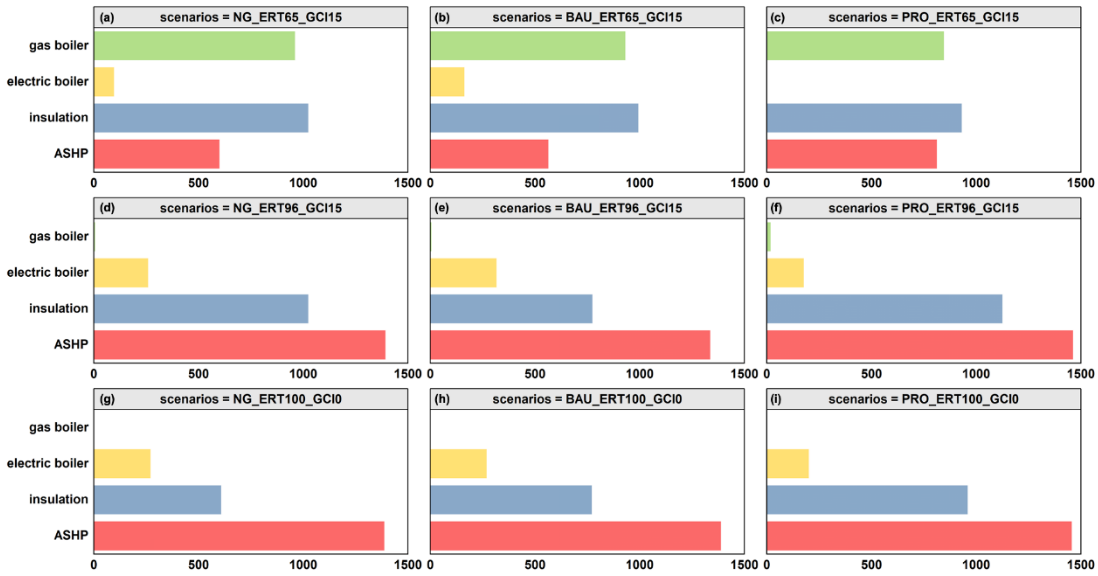


Figure13: Installation numbers of system optimisation measures under different scenarios

5.4.1 Combination A: GCI 15 gCO_2e/KWh and ERT 65%

When comparing the three policy scenarios, ERT 65% is the lower feasible limit of *PRO*, and the combination of ERT 65% and GCI 15 gCO_2e/KWh is quite close to current decarbonisation targets of Surrey. Figure 13(a-c) presents the choices of heating technologies and number of instalments for each policy scenario, in which there are still a large number of gas boilers installed. In this combination, if the priority is minimising costs to households, *PRO* is highly recommended, with an annualised households cost of £ 400,307 and annualised WBC cost of £ 234,804. It is noted that this scenario has the highest total cost of £ 1,704,706 since more ASHPs are installed. While if we target at achieving the GHG emission reductions with least total cost, *NG* has the lowest total annualised cost of £ 1,501,108. This solution contains fewer electric boilers and ASHPs, but the increased burden is transferred to households (£ 454,276) and WBC (£ 1,046,732).

5.4.2 Combination B: GCI 15 gCO_2e/KWh and ERT 96%

If GCI remains the same and higher emission reduction rates are expected, the highest feasible ERT is 96%. While this combination comes with the highest total cost as well as household cost for all the combinations of GCI and ERT for all 3 policy scenarios. As Figure 13 (d-f) depicts, no gas boiler is installed under *NG* and *BAU*, and *PRO* provides a solution with the most ASHPs and insulation measures, but the fewest electric boilers. To reduce the burden on households, *PRO* displays the lowest annualised cost of £ 685,837 and *BAU* has the highest cost of £ 885,698. Also, *PRO* has the least financial burden on WBC (£ 772,894). when comparing annualised total cost, *NG* is still the best choice (£ 244,1719) for 96% of emission reduction from gas and electricity, but the cost burden is shifted to WBC with £ 1,691,903 per year.

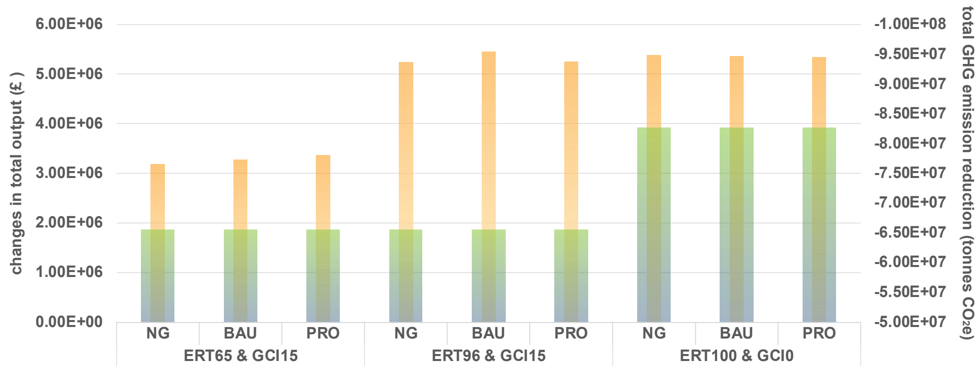
5.4.3 Combination C: GCI 0 gCO_2e/KWh and ERT 100%

To achieve Net-Zero, long term strategies could be expected that GCI should be 0 gCO_2e/KWh and GHG emission from gas and electricity should be reduced 100%. This combination has lower annualised GHG reduction cost if compared with the combination 5.4.2, and no gas boilers are installed for all 3 policy scenarios. *PRO* still has the lowest annualised household cost (£ 716,505), but unlike the former two combinations, *BAU* presents the lowest annualised total cost (£ 2,448,838). Decisions would be different when the priority stakeholder changes, and for *PRO*, there would be a £ 1,071,101 grant cost per year and the annualised cost for WBC is £ 763,833.

5.4.4 Impacts of different combinations

Changes in total output of whole economy system and total GHG emission reduction compared with baseline are also important aspects in making combination choices (Figure 14). Increases in total output under combination ERT 96% and GCI 15 gCO_2e/KWh (B) and combination ERT 100% and GCI 0 gCO_2e/KWh (C) are all higher than combination ERT 65% and GCI 15 gCO_2e/KWh (A) under all 3 policy scenarios. As for total GHG emission reduction, combination C has the largest emission reduction, and the emission reductions of the other 2 combinations are similar to each other.

Combination A and C have lower unit GHG emission reduction total cost, as well as unit household cost, than combination B. Thus, combination B is the least recommended decarbonisation target. For combination A, £ 1.71 million total annual investment in heating and energy system will bring about £ 3.37 million increases in total output of whole economy under *PRO*. The total GHG emission reduction is 65.51 million tonnes of CO_2e. For future equitable Net-Zero distributed heating systems, combination C outperforms combination B for higher total GHG emission reduction under similar total cost and increases in total output. Under *PRO*, total annual investment of £ 2.55 million will increase £ 5.33 million in macro-economic total output with 82.72 million tonnes of CO_2e emission reduction.



	ERT65 & GCI15 NG	ERT65 & GCI15 BAU	ERT65 & GCI15 PRO	ERT96 & GCI15 NG	ERT96 & GCI15 BAU	ERT96 & GCI15 PRO	ERT100 & GCI0 NG	ERT100 & GCI0 BAU	ERT100 & GCI0 PRO
total output	3.18E+06	3.27E+06	3.37E+06	5.23E+06	5.46E+06	5.24E+06	5.37E+06	5.35E+06	5.33E+06
total GHG reduction	-6.55E+07	-6.55E+07	-6.55E+07	-6.55E+07	-6.55E+07	-6.55E+07	-8.27E+07	-8.27E+07	-8.27E+07

Figure14: Changes in total output and total GHG emission reduction under different scenarios compared with baseline

6. Limitations and implications

To start with, the cost of reducing the carbon intensity of grid electricity is not included in this study, only equipment replacement, insulation, gas bills, and electricity bills are included. In this way, the cost for optimising the heating and energy system would be underestimated. Secondly, whole economy impact simulation is simplified by limiting the household consumption changes directly related with heating activities. Other indirect changes caused by the disposable income and substitutions are neglected. Also, the impact simulation is based on annualised total cost while the initial investment in the first year would have larger impact than the following years. Future work would be conducted in developing a dynamic model to reflect the changes in economic and environmental impacts more accurately.

In summary, decarbonisation of heating and energy systems is a significant piece in the whole picture of Net-Zero, and the transition to Net-Zero heating might increase the number of households in fuel poverty due to the inevitable additional costs. Thus, the case study in Woking of system optimisation for delivering affordable heating for households would shed light on other regions in the UK when proposing strategies to tackle fuel poverty.