Cities dilemma: cutting carbon emissions or alleviating poverty?[*][†]

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May 13, 2022

Abstract

The city of Bristol has committed to reduce carbon emissions and intends to be a leading example in this matter. The city also aims to generate the most benefits to its inhabitants and notably to reduce fuel poverty. The Bristol City Leap (BCL), a vast public procurement program, embeds series of energy investments opportunities to decarbonize infrastructures. However, some projects can have adverse effects on consumers, which raises a trade-off in the prioritization of objectives. With limited financial resources, the city faces a complex decision-making problem, requiring a careful analysis of the impacts of different project options. This paper provides an ex-ante assessment of the cost-effectiveness and the distributional impacts of BCL's projects in residential heating using a Cost-Benefit Analysis approach. Two projects are considered in the assessment: (1) a district heating network implemented in central districts and (2) energy efficiency retrofits for the least efficient dwellings. We build an original model that estimates the impacts of each project relative to a status-quo. The model is based on Energy Performance Certificates data and incorporates under-investment in energy efficiency and rebound effects. The results suggests that energy efficiency retrofits generate lower social welfare than heating networks. Energy efficiency retrofits would have a higher socio-economic Net Present Value if end-users behaved optimally and fully invested in retrofitting measures.

Keywords: Residential heating, energy efficiency, district heating networks, cost-benefit analysis

1 Introduction

Facing the emergency of climate change, cities have committed to achieve net zero carbon emissions through Climate Action Plans, see for instance New York's OneNYC Plan or Paris Climate Action Plan. These plans define series of investments to decarbonize infrastructures. In the building sector for instance, which accounts for one-third of countries' domestic emissions, cities can notably improve energy efficiency or use low-carbon technologies. Through these projects, cities also aim to improve the well-being of its inhabitants and in particular to reduce fuel poverty. Indeed, 10% of UK's households suffer from fuel poverty and cannot afford minimum standards for indoor heating according to the Annual Fuel Poverty Statistics in England (2020). However, some projects can have adverse effects on consumers, which raises a trade-off in the prioritization of objectives set by cities. In a context of scarce financial resources, cost-effective pathways must be identified to decarbonize

[*] **Work-in progress paper**

[†] **Aknowledgments:** I thank the participants of the 2nd Society for Benefit-Cost Analysis European Conference. I thank the comments from Carine Staropoli (PSE, Paris 1), Nicolas Astier (PSE, ENPC) and Philippe Gagnepain (PSE, Paris 1)

and to generate the highest benefits for citizens, posing a complex decision-making problem.

To address this trade-off, methods are necessary to carefully analyze the impacts of different projects. This paper provides an ex-ante assessment of the cost-effectiveness and the distributional impacts of projects in residential heating based on a Cost-Benefit Analysis approach.

The assessment is applied to the city of Bristol in the UK. The city of Bristol aims to be at the forefront of local authority-level action. The Bristol City Council plans to invest over £1 billion investment with the Bristol City Leap (BCL), a public procurement program, and has identified a series of projects in renewable energy, electric mobility, waste management and residential heating BCC (2020). Through these investments, the city aims to achieve carbon neutrality by 2030 while generating co-benefits, mainly reducing fuel poverty. This paper focuses on two projects in residential heating envisaged by the BCL: (1) district heating networks implemented in central districts and (2) energy efficiency retrofits for the least efficient dwellings in the city. Each project respond to different political and industrial processes. District heating networks are systems that distribute heat to buildings through a closed loop network carrying hot pressurized water coming from plants using different energy sources (waste, biomass, heat pumps or gas). Heating networks involve important capital costs and significant operation services. They are usually implemented by cities through public private partnerships to lever private capital and expertise. Energy efficiency retrofits consists of improving the performance of buildings through insulation measures (cavity walls, double glazing or roof insulation). Cities can directly implement energy efficiency retrofits on their buildings stock, and incentivize private dwellings through different mechanisms such as subsidies, or loans.

Socio-economic assessments of projects in residential heating present a number of concerns. First, energy efficiency retrofits are subject to various market failures implying an "energy efficiency gap": individuals decisions about energy efficiency lead to an under-investment in energy efficiency measures and lower adoptions than expected (Gillingham and Palmer (2020); Fowlie et al. (2018)). Second, energy efficiency retrofits involve a rebound effect at end-users' side. After a retrofit, end-users spend less for the same service level and can improve their comfort by increasing their energy consumption. This surge in energy consumption implies a backslash in the predicted energy savings and thus in saved carbon emissions. Conversely, heating systems upgrades can imply a higher price charged to end-users, reducing their surplus and reducing further carbon emissions than predicted due to the elasticity of heating demand (Sorrell et al. (2009)). Third, building-physics energy models traditionally conduct their assessment by computing dwellings' energy consumption based on the building envelope and by applying normative assumptions on households occupancy and behavior, see for instance the Standard Assessment Procedure in the UK SAP (2012). These models fail to the depict reality and overestimate the consumption and energy savings actually realized by households (Brøgger et al. (2019)).

This paper aims to address these issues by providing a socio-economic assessment that better estimates the outcomes of residential heating projects and reduce potential shortfalls. To do so, the paper presents a model that estimates ex-ante the impacts generated by projects scenarios against a status-quo. The model is calibrated on the Energy Performance Certificates (EPC)[1] data and addresses biases stemming from building-physics models (SAP (2012); Brøgger et al. (2019)). Besides it incorporates economic and behavioral processes based on the literature, namely energy savings shortfalls, demand elasticity and rebound effects (Gillingham and Palmer (2020); Giraudet et al.

[1]Registers for domestic buildings Energy Performance Certificates providing energy efficiency ratings at the dwelling level and heating characteristics, accessed from the Ministry of Housing Communities and Local Government's Open data communities platform

(2021)). Impacts on carbon savings, heating costs and comfort gains are estimated at the dwelling level and aggregated with financial costs and revenues in socio-economic Net Present Values (NPV). Two types of projects are designed based on the BCL tender and provisional plans from an energy service company participating to the procurement process in order to get close to city's expectations.

This paper intends to make several contributions to the literature and makes some policy recommendations. First it presents a sound and flexible economic assessment model that integrates several projects in residential heating. To our knowledge there is a lack of studies comparing projects improving energy efficiency and using low carbon technologies in the same assessment. Giraudet et al. (2021), use an energy-economy model to assess the cost-efficiency of different policies in energy efficiency. Charlier and Risch (2012) evaluate the impacts of energy savings measures integrating individuals decision to retrofit their dwelling. Other papers conducting CBA for district heating networks projects focus on specific technologies (Feng et al. (2021); Leurent et al. (2018); Groth and Scholtens (2016)). Spirito et al. (2021) study the interactions between district heating networks and energy efficiency, but focus on the the economic viability of the district heating network. Second, our model addresses the limits of building-physics models for assessing energy-savings potentials. Previous studies have documented the upper bias in building-physics models (Cuerda et al. (2020); Cozza et al. (2021); Brøgger et al. (2019)). We study the shortfall between potential heating savings and actual heating savings with EPC data. Our paper will identify retrofitting measures not implemented by end-users due to under-investments in energy efficiency[2].

Third, we find that the energy efficiency retrofits program is the most cost-effective option, delivering higher benefits per pound invested. Conversely, heating networks achieve more carbon emissions and consumers surplus per dwelling with a higher marginal cost. This suggests that, while energy efficiency retrofits should be implemented first under limited financial resources, district heating networks are required to decarbonize more deeply the building stock and get closer to the city's objectives. However district heating networks have a negative effect on rental tenures, likely to pertain to lower income levels. Thus, cities should find compensation schemes to prevent regressive effects when implementing capital intensive low carbon technologies.

The rest of the paper is structured as follows. Section 2 sets the CBA applied to the Bristol case study, section 3 describes the methodology used to construct the model. section 4 presents the CBA results and section 5 concludes.

2 Cost-Benefits Analysis: application to Bristol

A Cost-Benefit Analysis (CBA) is conducted to assess the project options to be carried on by the city (Quinet (2013); HM Treasury (2020); Atkinson and Mourato (2015)). A CBA provides a socioeconomic Net Present Value (NPV) of a project by discounting social costs and social benefits generated through its lifetime relatively to a status-quo scenario. It requires baseline assumptions, setting the context in which the study takes place, a status-quo scenario, including actions implemented by the city if not selecting the projects, and project scenarios, detailing the scope of measures taking place under each option, as described in this section.

[2]This part is still in progress and is not included in this version

2.1 Baseline and Status-quo scenario

2.1.1 Status-quo scenario

The status-quo scenario aims to pursue the city's commitments in energy efficiency. More than 10,000 private and public housing have been retrofitted in Bristol since 2010 (BCC (2020)). Buildings were retrofitted either through government schemes such as the Energy Company Obligation, subsidy paid by energy suppliers, and the Green Deal, government loans, or were supported by local schemes such as the "Warm Up Bristol" initiative, a grant program. In spite of the "Warm Up Bristol" program closing in 2017, the city has identified more than 90,000 domestic homes eligible for energy efficiency and targeted 7,000 social housing that must reach a C grade in energy efficiency or above in latest strategy reports (Foster et al. (2018); Roberts et al. (2019)).

It is assumed that without the projects option, the City Council would take minimal initiatives to maintain the rates of renovation completed over the past ten years. Between 2008 and 2018, 7.6% of the housing stock as been retrofitted, corresponding to an annual rate of 0.32% for social housing and 0.09% for private housing, according to the analysis of dwellings' Energy Performance Certificates (EPC) over time. By extrapolating these trends, the status-quo scenario comprises 976 social dwellings and 1,676 private dwellings to be retrofitted between 2021 an 2050 independently of their energy efficiency labels. These retrofits are done through local initiatives and are therefore accounted for in the City Council's budget.

Considering low carbon heating systems. The status quo scenario assumes no future deployment of heating networks. The Bristol City Council would remain with the existing 5 MW of capacity installed in Bedminster and Castle Park districts. The two heating networks currently supply 1,000 dwellings over a potential of 68,000 buildings (Foster et al. (2018)). There are plans to expand existing networks and connect new buildings. However, this includes administrative and commercial buildings being outside the scope of the study.

2.1.2 Baseline and trends

The baseline energy efficiency level and characteristics of the Bristol housing stock are obtained from Energy Performance Certificates at the dwelling level. A data-set depicting the most recent picture of Bristol's build stock as of 2020 is constructed by selecting most recent EPC observations per dwelling, as presented in Section 3.

The Bristol housing stock is kept constant through 2050. New housing is expected to be build in Bristol by next decades with more stringent energy efficiency standards (Foster et al. (2018)). However this does not interact with the projects or the status-quo scenarios. New housing stock is considered as an exogenous trend that occurs independently of the study. If accounted in the baseline trends, the impact of the housing stock would be netted in the assessment, being common to the status quo and the project scenarios (impacts computed as the difference between the two).

Baseline energy prices are taken from the Standard Assessment Procedure data-base, the framework that defines guidelines for EPCs SAP (2012), matching the housing stock characteristics. The SAP database displays retail prices from 2008 to 2021 for different energy sources used in residential heating, see Appendix A. It sets the price of electricity and gas at £18 per MWh and £4 per MWh in 2020, which is in line with the BEIS' "Quarterly Energy Prices Report" (BEIS, 2021).

The assessment then sets long-term energy prices trends. A first approach consists in extrapolating price trends observed before 2020 obtained in previous BEIS reports, corresponding to rates of 1% p.a. and 2% p.a. for electricity and gas through 2050. These trends are similar to the ones taken in the paper by Giraudet et al. (2021) carrying the same exercise. However there are currently great uncertainties for long-term energy prices, stemming from international crises (Covid-19, Ukraine war), inflation, and latest IPCC reports. Settling long-term energy price trends in this context is a complex exercise that requires specific forecasting models. This paper will conduct the CBA on various price trends. The low trend hypothesis follows the rates obtained in the initial approach, whereas the high trend hypothesis is based on observed rates in the UK short-term energy retail market (Ofgem, 2021). An intermediary trend is settled in between, as detailed in table 1.

Table 1: Energy retail price trends considered in the assessment, fuel source categories taken from SAP (2012)

Annual Price trends 2022–2050	**Electricity**	**Gas**	**Oil**	**LPG**	**Wood**	**Heat Networks**
Low	0,01	0,02	0,02	0,02	0,005	0,006
Middle	0,02	0,05	0,05	0,05	0,0125	0,015
High	0,04	0,1	0,1	0,1	0,025	0,030

Life cycle carbon emissions factors for each energy sources are taken from the SAP database. These factors are cross checked with other databases from the BEIS and the ADEME on greenhouse emissions (see Appendix A). The assessment settles a trend on carbon emission factors in line with UK government's decarbonation commitments. The government has set an objective to reduce by 20% the UK's electricity grid emissions by 2050, implying a rate of 0.8% per annum (BEIS (2021)). Current EU directives aim at reducing gas life-cycle emissions by 1% per annum. Biomass energy sources are assumed to stay constant through 2050 as in the Giraudet et al. (2021) assessement.

2.2 Project scenario 1

Project 1 comprises the connection of 5,511 dwellings in Bristol central districts to district heating networks. A list of district heating networks to be build is obtained form the Bristol City Council[3] BCC (2020).

A provisional planning for infrastructure works and new dwellings connections is provided by a heat network developer bidding for the Bristol City Leap. In each targeted district, it is assumed that the district heating network will only connect dwellings located in apartments. Indeed, district heating networks are economically viable in most densely heated areas and minimize the distance per connected household prioritizing multi-family housing and apartments Lund et al. (2014).

The heat networks' overall energy mix is obtained from the developer's proposal and is composed of the following: heat pumps accounting for 54% of the energy mix, with a $COP = 3$, a combined heat and power plant accounting for 25% of the energy mix and an efficiency of 85%, a biomass plant, 10% of the energy mix with an efficiency of 90%, peak gas boilers, 11% of the energy mix and an efficiency of 90%.

The district heating network price scheme is based on a fixed and a variable component and the operator's required return on capital, respectively 45£/kW.year and 0.055 £kWh, resulting in an

[3]Old Market, Redcliffe, Temple, Bedminster, Spike Island, Frome Gateway, University of Bristol, Bristol Royal Infirmary, City Centre, Ashton Gate in the following postcodes: BS1, BS2, BS3, BS5, BS8

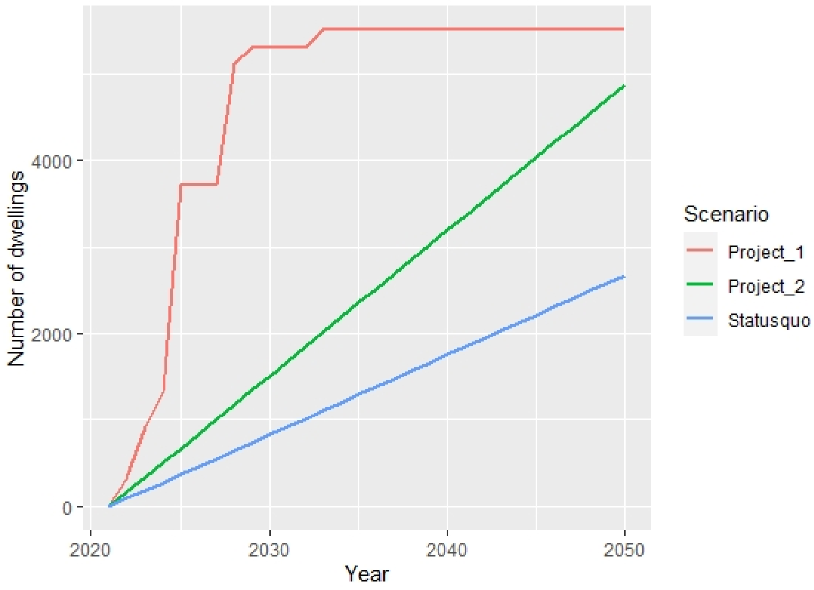


Figure 1: Dwellings' connections and upgrades in each scenario

average of 0.07 £ per kWh [4].

2.3 Project scenario 2

Project 2 is a large retrofitting program for all dwellings with an energy efficiency label less than D covering the whole Bristol area, in line with City Council's goal of banning all housing being rated under D by 2050 (Foster et al. (2018)). Dwellings are retrofitted at different rates according to their tenure type. Social housing being mostly owned by the city are retrofitted with a turnout of 80%, while least efficient private housing being subject to individuals preferences are retrofitted at a rate of 25% (Gillingham et al. (2009)). This corresponds to 1,126 social housing and 3,747 private households.

The City Council supports energy efficiency retrofits by subsidizing private housing and directly financing social housing. Retrofitting costs estimates are taken from Giraudet et al. (2021), and are displayed in Appendix B. After being converted to £2020, it ranges between 65 and 380 $£.m^{-2}$ and is given conditional on the level of improvement (e.g. from D to B). The subsidy mechanism is scaled proportionally to the total retrofitting cost and ranges from £5,000 to £10,000 according to the dwelling.

Figure 1 below shows the connection timelines taken in each project scenario and in the status-quo.

2.4 Price of carbon

CBA requires a proxy to monetize the social cost generated from one equivalent ton of carbon (Bureau et al. (2020); Atkinson and Mourato (2015)). Several carbon prices are used in the assessment, following different approaches.

[4] fixed annual charge divided by the mean heating hours during a year, 2555 hours in South West England

First, the carbon price is aligned with the carbon market. The actual UK ETS trigger price amounts at $45.9 £ per.ton$ (BEIS (2021)), and would grow at a rate of 4%[5]. Second the carbon price is set at the social cost of carbon obtained from integrated assessment models (Nordhaus (2018)). Recent estimates of the social cost of carbon amonts to 133 $.2010 in 2020 for a discount rate of 2.5% (Nordhaus (2018)). Third, the carbon price is aligned with the shadow price of carbon displayed by the IPCC (2018) required to meet temperature increase scenarios. IPCC (2018) has set different shadow prices of carbon to stay in a 1.5°C scenario with some probabilities. The carbon prices corresponding to the low and the high probability scenarios are used in the assessment.

Table 2 below summarizes the different carbon prices used in the assessment. A sensitivity analysis will compare the results of the assessment under each carbon price. The default carbon price is aligned with the social cost of carbon provided by Nordhaus (2018), providing an intermediate value for our analysis.

Table 2: Carbon prices estimates taken in the assessment

Carbon prices in £.2021	**Year 2021**	**Year 2050**
UK ETS market - BEIS (2021)	45.9	100
DICE model - Nordhaus (2018)	106	194
1.5°C Scenario low - IPCC (2018)	161	821
1.5°C Scenario high - IPCC (2018)	753	3182

2.5 Social discount rate

The socio-economic Net Present Value (NPV-SE) discounts social costs and social benefits with a discount rate, noted d. The CBA follows the recommendations from the UK framework for CBA and uses a social discount rate for risk free projects set at 3.5%.

3 Methodology

This section presents the model constructed for the assessment. The model estimates future annual heating demands (in kWh) at the dwelling level upon the completion of a project: involving a change in heating system (Project 1) or an energy efficiency improvement (Project 2 and Status-quo). Annual heating demands are estimated on the period $2020 - 2050$. Impacts are computed each year at the dwelling level by comparing the new heating demand with the counterfactual heating demand, that occurs without the project uptake. Four annual impacts are aggregated in the model:

- Consumers' surplus: difference in expenditures at the dwelling level
- Comfort savings: difference in internal temperature proxied by heating consumption
- Carbon social cost: reduction in carbon emissions monetized with carbon price (Section 2.4)
- Project net costs: difference between annual revenues and annual costs in each scenario

Heating demands are calibrated using rebound effects and elasticity estimates differentiated at the tenure type. Different tenure categories are: owner-occupied, rental (private), and rental (social). This allow us to investigate distributional impacts. The relationship between income levels and

[5]projected market carbon price of 100£/ton in 2050 against 30£/ton in 2021, implying a 4 % increase per year LSE, 2019; CCC's Case for Net Zero, 2019

home-ownership are well documented Stephens and Leishman (2017); Lersch and Dewilde (2018)). Besides, there is significant heterogeneity when estimating rebound effects and price elasticity conditional on tenures types. Aydin et al. (2017) analyse the rebound effect of the residential heating and finds rebound effects significantly lower for owner-occupied dwellings than rental dwellings. Madlener and Hauertmann (2011) study the price elasticity of the residential heating conditional on the tenure and obtain a similar difference in the results. This in line with the fact that higher income level households are less sensitive to costs changes of the heating service, as outlined in McCoy and Kotsch (2021).

The model relies on a data-set representing Bristol's housing stock in 2020 that gives initial heating demand and characteristics at the dwelling level (Section 4). The model updates the building housing stock each year by selecting random batches of dwellings conditional on their location, property type, tenure or energy efficiency rating. The batch size corresponds to the timeline settled in each Project scenario. The simulation is repeated 10 times in a Monte Carlo experiment.

3.1 Heating demand function

The heating demand for dwelling i at year t and under scenario s is noted $E_{i,t,s}$. Equation (2) and eq. (1) give the generic function for the heating demand (in kWh) after both an energy efficiency uptake, in case of the Project 2 ($s = 2$) or the Status-quo scenario ($s = 0$), and a replacement of the heating system in case of Project 1 ($s = 1$).

The heating demand function is recursive, as it applies an annual trend to the heating demand obtained at the previous year $E_{i,t-1}$. Energy retail prices $P_{i,t,s}$ and price trends $r_{i,t,s}$ are specific to the dwelling's energy source and depends on the scenario in play. In case of scenario $s = 1$, the dwelling shifts its heating system and experience a price change from P_{i,t,s_0} to P_{i,t,s_1}. In scenarios $s = 0$ and $s = 2$ the dwelling benefits from heating savings noted $K_{i,s}$. The heating demand range in an interval defined by two thresholds. $\underline{E}$ is the minimum consumption level and $\overline{E}$ is the maximum service level required by the end-user to live in decent conditions.

ϵ and τ are respectively the heating demand elasticity and the rebound effect and will be parameterized in Section 4. ϵ gives the the percentage decrease of heating demand induced by one percentage point increase in price. τ gives the increase of heating demand induced by one percentage point increase in heating savings. In the same vein, heating savings $K_{i,s}$ are derived from the data (Section 4). $K_{i,s}$ are fixed over time since buildings' thermal envelope are assumed to stay constant in the 30 years time period without retrofits, in line with McCoy and Kotsch (2021).

$$E_{i,t,s} = \max\left(\min(E'_{i,t,s}; \overline{E}); \underline{E}\right) \tag{1}$$

$$E'_{i,t,s} = E_{i,t-1}(1 + \epsilon_i r_{t,s})(1 + r_{t,s})(1 + \epsilon_i(\frac{P_{t,s} - P_{t,s_0}}{P_{t,s}})(1 + K_{i,s}(\tau_i - 1)) \tag{2}$$

For heating demands' recursion to hold, we assume no exogenous shocks in households' preferences and a strong path dependency. The heating demand function is defined as a linear function for simplicity. The model could be extended by incorporating non-linearities near threshold levels using a logistic specification.

Consumers' surplus $CS_{i,t,s}$, reduction in carbon social cost $CO2_{i,t,s}$ and projects net costs $PS_{t,s}$ are given in eq. 3-5 below, and are then used to compute the Projects' socioeconomic Net Present Values $NPV.SE_s$ in Eq. 6.

$$CS_{i,t,s} = E_{i,t,s_0} P_{t,s_0} - E_{i,t,s} P_{t,s} \quad (3)$$

$$CO2_{i,t,s} = (E_{i,t,s_0} F_{t,s_0} - E_{i,t,s} F_{i,t,s}) PCO2_t \quad (4)$$

$$PS_{t,s} = \sum_{i}^{N} E_{i,t,s} I(h_i = 1)_t P_{t,s} - (I_{t,s} + C_{t,s}) \quad (5)$$

$$NPV.SE = \sum_{t=2}^{31} PS_{t,s} + \sum_{i}^{N} \frac{CS_{i,t,s}}{(1+d_t)^t} + \frac{CO2_{i,t,s}}{(1+d_t)^t} \quad (6)$$

$F_{i,t,s}$ are carbon emission factors corresponding to the heating system of dwelling i. $I(h_i = 1)_t$ is a dummy variable that indicates if dwelling i's is connected to a heating network. Cash flows are discounted with d_t (Section 2.5).

Finally, the impact on comfort at the dwelling level $H_{i,t}$ is approximated by the difference in the heating consumption and monetized with energy retail prices. This holds under the assumption that any change in heating consumption stems from variations in internal temperatures (in progress).

$$H_{i,t,h_1,ee} = (E_{i,t,h} - E_{i,t,h_1,e}) P_{t,h} \quad (7)$$

3.2 Calibration of the model (in progress)

3.2.1 Rebound effects

Rebound effects have been the subject of intense research activity in recent years, involving a wide range of definitions and methodological approaches (Sorrell et al. (2009)). The rebound effect in this paper corresponds to the part of the incremental energy demand attributed to an increase in the mean internal temperature after the retrofit of the dwelling. This effect is documented as the "temperature take-back factor" and is measured as the elasticity of the energy consumption relative to the actual energy gains from a retrofit. This estimate is lower than the total shortfall observed between actual energy savings and theoretical energy savings predicted by the engineer. Indeed, studies estimating the rebound effect, such as Aydin et al. (2017) and Coyne et al. (2018) are based on expected energy gains stated by the EPC assessor and do isolate the channel of the rebound effect caused by an increase of the heating service consumption. The resulting estimates present and upper-bias due to the systematic shortfall between theoretical energy savings and actual energy savings. Fowlie et al. (2018) study the rebound effect of the residential heating demand through a Randomised Controlled Trial and fail to find evidence of significantly higher indoor temperatures, attributing most of the observed rebound effect to the engineer overestimation bias.

The rebound effect is calibrated using past studies of the temperature take-back factor. Sorrell et al. (2009) conducted a large literature review on the rebound effect in various sectors and find temperature take back factors of the residential heating demand ranging from 0.05 to 0.3 with a mean around 0.2. Hamilton et al. (2011) study temperature take-back factors through an experiment and find a mean estimate of 6% of potential energy savings that could reach 22% for least efficient households. Hediger et al. (2018) apply a stated preference approach on Swiss households to estimate the compulsory increase in service consumption implied by an energy efficiency retrofit and find values ranging from 0.10 to 0.14. The values from Hamilton et al. (2011) are used to calibrate the model.

3.2.2 Price elasticity

The price elasticity parameter corresponds to the elasticity of energy demand with respect to the energy price. The rebound effect and the price elasticity are dissociated to avoid an overestimation of each effect due to simultaneous changes in prices and investment costs induced by different projects, as well as to account for different behaviors between prices increase and a costs decrease, and to control for potential selection biases of households self-selecting in energy efficiency programs to improve their service level (Sorrell et al. (2009)).

Sorrell et al. (2009) provides a range of $0.10 - 0.58$ for the price elasticity of the heating demand relative to cost decreases. However estimates can be confounded with rebound effects. Labandeira et al. (2017) study price elasticities from a meta-regression analysis of 428 papers produced between 1990 and 2016. Price elasticity estimates are different according to the fuel source being -0.18 for gas and -0.13 for electricity. Chitnis et al. (2014) separate the relative contribution of income and substitution effects and find lower estimates; -0.09 for gas and -0.07 for electricity. Mean values from Labandeira et al. (2017) are taken to calibrate the model.

Table displayed in Appendix C presents a review of the elasticity estimates obtained by the literature.

3.2.3 Energy consumption thresholds

Maximum heating consumption levels are obtained from the standard consumption displayed in the EPCs. Indeed the EPC indicates the standard consumption of a dwelling under 21°C. It is assumed that the dwelling maximum consumption is the EPC standard consumption multiplied by a factor of 1.2. Considering the minimum energy consumption threshold, the value is currently set at 0.

3.3 Data

The model relies on a housing stock, a data-set that elicits heating demand and other characteristics at the dwelling level in 2020. The housing stock is constructed from the Energy Performance Certificates (EPC) data[6] that covers more than 14 million dwellings in the UK, identified at the address level. Each dwelling has several observations providing the following variables:

- Current and potential energy efficiency ratings (EPC bands) – ranging from A to G
- Current and potential standard heating expenditures for hot water and heating appliances. These figures are obtained by applying the Standard Assessment Procedure (SAP) methodology, a building-physics model
- Heating systems and fuel sources
- Property types: flat, detached dwelling, semi-detached dwelling
- Tenure categories: owner-occupied, rental (private), rental (social)
- Total floor area
- Number of heated rooms
- Details on the energy efficiency envelope (e.g. double glazing, walls insulation, roof insulation)

The EPC data-set is curated and processed in order to obtain the most recent picture of the Bristol housing stock in 2020 by selecting most recent EPCs per dwellings. Dwellings with incorrect data are washed out (less than 1% of the observations) resulting in a data-set of $129,538$ observations. Standard heating expenditures in EPCs recorded before 2021 are actualised by the fuel price of the recorded year and the fuel price in 2020 to obtain energy consumption in 2020.

EPCs only offer a partial view of the housing stock and some caveats must be addressed. First, EPCs are completed by energy efficiency assessors, prone to idiosyncratic errors Gillingham and Palmer (2020). Second, EPC only provide estimates for the standardized energy consumption derived from the building-physics model. Theoretical energy consumption figures are likely to diverge from observed expenditures, falling to internalize behavioral or contextual factors (cite SAP). Third, the estimated potential energy consumption indicated by the EPC represents an upper bound of the savings that could be achieved by a dwelling after implementing the recommended retrofitting measures Brøgger et al. (2019). Dwellings are likely to implement only a part of the retrofitting measures and thus achieve less energy savings as expected. The following describes the strategies employed to correct for theses sources of bias in the data-set.

[6] Ministry of Housing Communities and Local Government's Open data communities platform

3.3.1 Estimation of real energy consumption

The SAP methodology computes standard energy consumption based on the dwelling envelope – e.g. space heating requirement, ventilation rates, walls heat transmission – and for a defined level of temperature set at 21°C. Such model is good to compare different dwellings on a similar basis but do not account for individuals preferences.

Research papers studying energy use in buildings have studied the discrepancy between building stock energy models and actual energy consumption (Cuerda et al. (2020); Cozza et al. (2021); Brøgger et al. (2019)). All papers outline a shortfall between actual and theoretical energy consumption's and an overestimation form the building-physics model. Some papers have investigated ways to provide better estimates for actual energy consumptions. Brøgger et al. (2019) implement a multiple regression analysis to develop a model predicting actual energy consumption from building-physics models with actual energy consumption data in Denmark. Cozza et al. (2021) estimate real energy consumption based on locational factors and households' detailed characteristics of the household. However, no meta-analysis or econometric models applied on the UK case have been fund.

In this paper, standard consumptions are corrected by applying a random variable to each observation corresponding to the shortfall between theoretical and actual consumption. The distribution of the random variable is derived from the BEIS Quaterly Energy Price report issued in 2018 (BEIS, 2018), which compares actual consumption from the English Households Survey and standardized energy consumption from the SAP. A systematic overestimation is fund conditional on households income levels and dwellings EPC band. The difference variable correcting the model follows a normal distribution with a standard error of 100 £ and means as reported in Table 3 – mean differences reported per EPC band and income levels. Figure 2 displays the distributions of the theoretical energy expenditures and of the estimated actual energy expenditures.

Table 3: Expenditure difference (theoretical - actual consumption) according to EPC band and income level (in £)

	All Households		**Fuel Poor households**	
Label	**Absolute difference (in 2018 £)**	**Percentage difference**	**Absolute difference (in 2018 £)**	**Percentage difference**
A	0	0	0	0
B	0	0	0	0
C	68	6%	220	16%
D	135	10%	280	20%
E	281	22%	409	27%
F	510	36%	758	47%
G	510	36%	758	47%

3.3.2 Estimation of actual heating savings

A panel econometric specification is estimated to study the shortfall between potential heating savings, estimated ex-ante, and actual heating savings obtained from the standards energy consumption of the two EPCs (before and after a retrofit). The estimation is based on all dwellings with multiple EPCs recorded in the UK's Southwest region. It is observed that achieved energy savings after implementing a retrofit is significantly lower than the potential heating savings recorded ex-ante. Details and results of the reression are reported in Appendix D.

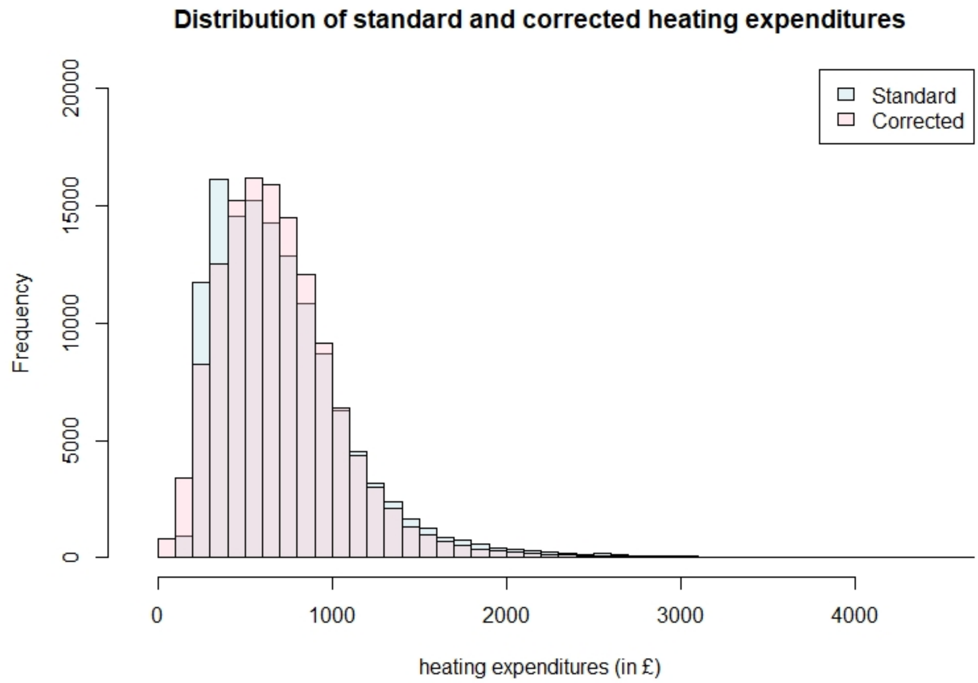
Dwellings that undertake a retrofit achieve on average 34.1% of the potential heating savings stated ex-ante by the engineer. This shortfall is heterogeneous according to the socioeconomic level. Private rental households achieve more savings per potential savings as compared to owner occupied households while social rental households achieve less savings per potential as compared to owner-occupied households. Besides, the regression results indicate a positive trend in the standard consumption reported in the EPC. Standard consumption on average are 33.8% higher in latest EPCs than former ones (with no energy efficiency upgrades implemented).
The explanation for this systematic shortfall is that households do not implement all the retrofitting measures specified in the EPC. Alternatively, the SAP methodology could have been updated over the years and become more stringent over time, which increases the ex-post standard consumption. However the latest update of the SAP methodology dates from in 2012 and year fixed effects should control for time variant trends.

The econometric regression results allow the heating savings to be adjusted by applying a data generating process as follow:

$$Y_{i,c} = 0.019 + 0.273 * X_i + \lambda_c \quad (8)$$

Where $Y_{i,c}$ is the estimated actual heating and X_i is the potential heating savings identified at the dwelling level, λ_c is a constant specific to the tenure type (equal to 0 for owner-occupied, -0.073 for rental social and 0.022 for rental private tenures). The distribution of heating savings before and after correction is displayed in Figure 2.

Summary statistics of the resulting data-set are given in Appendix E conditional on the tenure type.



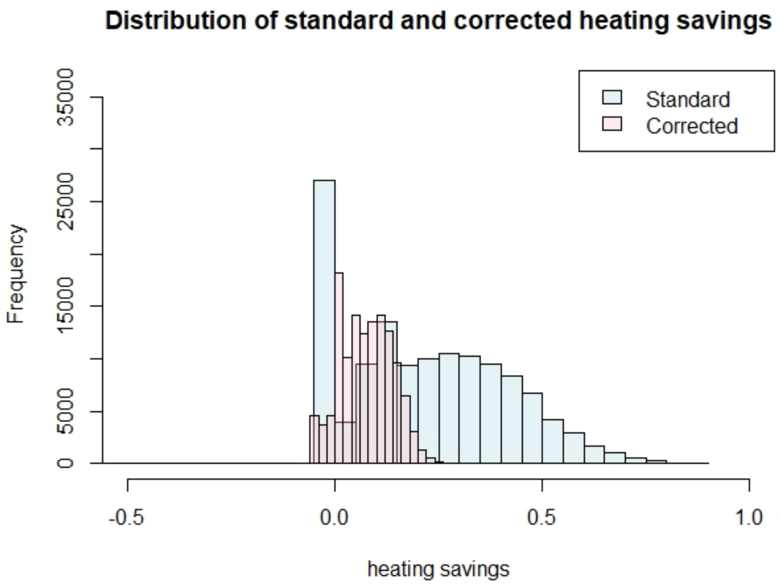


Figure 2: Distribution of heating expenditures and heating savings before and after the correction

4 Results (in progress)

4.1 Projects' Impacts and NPV

Figure 3 details monetized impacts generated by each scenario discounted in net present values. Project 1 is better at delivering carbon savings and consumers' surplus (noted expenditures savings in the graph) while Project 2 delivers higher comfort benefits. Project 1 saves three times more carbon than Project 2. Indeed, the district heating networks' energy mix has lower carbon emissions factors, 0.14 kg/kwh versus 0.24 kg/kwh for the electricity grid, benefiting from large heat pumps and a biomass plant. However, carbon savings in Project 1 decrease in time. The energy consumption reduction stemming from increasing energy prices is slower for users connected to heat networks than users with gas boilers, reducing the energy consumption shortfall induced by the switch from gas to heat networks over time. Besides, the electricity grid and natural gas decarbonize at a faster rate than heat networks, which is also contributing to decreasing carbon savings in Project 1.

Project 1 generates an incremental £ 2 million worth of consumers' surplus as compared to Project 2. Despite an increase in heating expenditures when switching from gas to heat networks during the first decade, end-users start to make heating expenditures savings as of 2037 when the price of gas becomes higher than the price of heat networks. The price difference in 2021 implies an increase by 77% of heating expenditures for users replacing their gas boilers, while it implies a reduction by 34% of their expenditures in 2050. Conversely, expenditures savings for end-users switching from electric heaters to heat networks increase with time, reduce their heating bills by 55% in 2022 and by 59% in 2050.

Project 2 delivers more than £ 1 million of comfort benefits in net present value, while Project 1 generates less than half that amount in comfort gains. The surge in heating expenditures experienced by end-users switching from gas to heat networks implies an important loss of comfort at the beginning of the time period. End-users that are formerly on gas have to decrease their heating demand as compared to the counterfactual and start to improve their comfort in 2039. Initially, end-users under gas heating consume on average more than end-users under electric heating, thus comfort benefits realized by the latter do not balance the loss of gas end-users at the beginning of the period as seen in the bottom-right panel of Figure 3. Conversely, Project 2 improves the comfort of end-users independently of the former heating source, reducing the cost of the energy service for all dwellings.

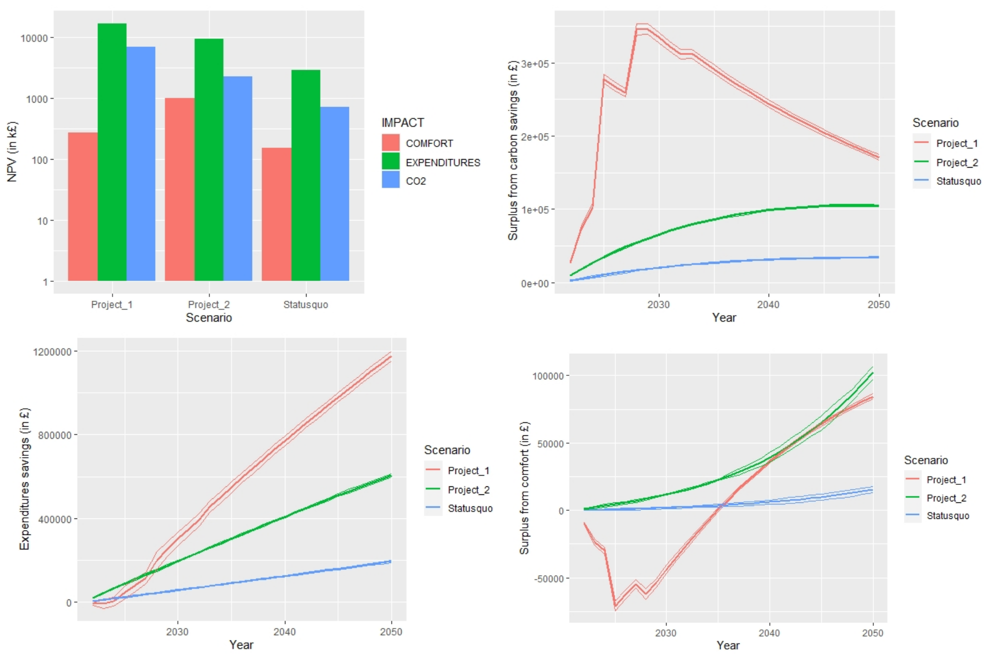


Figure 3: Monetized impacts generated in each scenario; present value with discount rate = 3.5%; social cost of carbon as a proxy

Figure 4 displays Net Present Values pertaining to the economic scope, noted $NET.NPV.ECON$, the financial scope, $NET.NPV.FIN$, and the socioeconomic scope, $NET.NPV.SE$. The NPVs of each projects are netted from the status-quo scenario.

Both Project 1 and Project 2 generate a positive socioeconomic NPV, with £ 15 millions and £ 1 million respectively. This result suggests that under current assumptions both projects produce more benefits than costs and should be undertaken by the city. Project 1 has a higher socioeconomic NPV. It achieves two times more economic impacts and has a higher financial NPV than Project 2. Indeed, the capital costs required by the district heating networks are balanced by revenues from heat sales during operations.

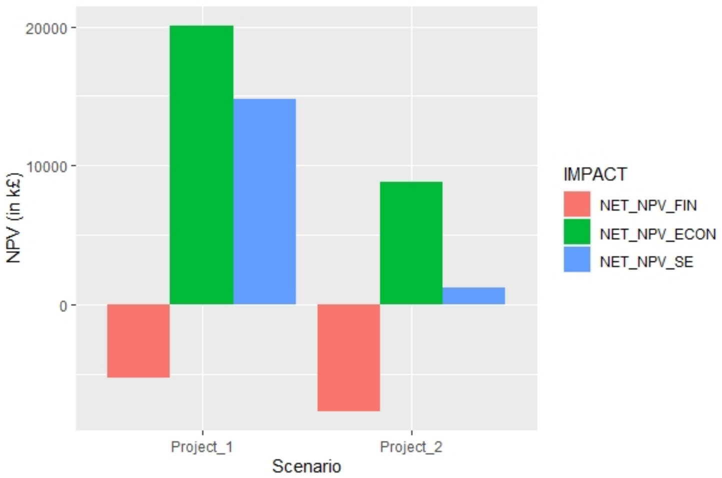


Figure 4: Net present values in 1,000 £

4.2 Heterogeneous Impacts

Table 4 displays impacts conditional on the dwellings' tenure type. Project 1 is targeting more rental private households, reaching 1,820 additional units as compared to the status-quo versus 612 additional units in Project 2. Conversely, Project 1 reaches less owner-occupied households than Project 2, 218 units versus 1410 units respectively, and is detrimental to social housing dwellings reaching 196 units less than in the status-quo. Indeed, heat networks connect central districts' dwellings grouped in apartments. Central districts apartments are less likely to be social housing and are more often occupied by private renting tenants. Project 2 comprises more owner-occupied dwellings since they are more likely to be under the energy efficiency band D.

Project 1 generates positive consumer surplus for social housing, despite targeting less dwellings than in the status-quo, but implies a loss of comfort for social housing tenures. Project 1 also implies a loss of comfort for rental private dwellings, while generating net benefits for owner-occupied tenures. Recall that price elasticities are set conditional on the tenure type. Owner-occupied tenures have lower price elasticities than rental tenures as they are less sensitive to change in the cost of heating. This difference in elasticity drives the difference in the impacts of Project 1. Owner-occupied reduce less their heating demand when switching to heating networks and thus realize higher gains when gas price exceeds heating networks prices. Since owner-occupied dwellings consume on average more energy than rental tenures (see Appendix E), the comfort gains of owner-occupied dwellings out-balance the loss of rental tenures in Project 1.

This result suggests that district heating networks have degressive impacts, improving the surplus of higher income households and decreasing the surplus of lower income households.

4.3 Cost-Effectiveness

Table 5 provides cost-effectiveness metrics, expressed both in monetary (impact per 1,000 £ invested) and in units (impact per year and dwelling) for each project. Consumer surplus is the sum

Table 4: Impacts for each tenures, NPVs are computed relatively to the status-quo; expressed in £

		Rental (social)	Rental (private)	Owner-occupied	Total
Project_1	N	7,82E+02	2,34E+03	1,28E+03	4,40E+03
	N net	-1,96E+02	1,82E+03	2,18E+02	1,85E+03
	Comfort NPV	-9,39E+04	-1,73E+04	1,12E+05	8,29E+02
	Consumers surplus NPV	1,83E+06	6,33E+06	2,01E+06	1,14E+07
Project_2	N	1,13E+03	1,13E+03	2,48E+03	4,73E+03
	N net	1,48E+02	6,12E+02	1,41E+03	2,17E+03
	Comfort NPV	1,49E+05	1,60E+05	5,21E+05	8,30E+05
	Consumers surplus NPV	5,85E+05	1,62E+06	4,05E+06	6,26E+06
(l)2-6					

of heating expenditures savings and comfort gains. Project 1 is more efficient at delivering benefits per dwelling while energy efficiency retrofits are more efficient per pounds invested. A social planner is thus induced to implement energy efficiency retrofits in priority, being the most cost effective option. However, heating networks imply 300 % more carbon savings and 60 % more consumers surplus than energy efficiency and are necessary to reach the City Council's net zero carbon emissions objectives.

Table 5 shows differences in cost-effectiveness metrics between the Project 2 and the Status-quo. Project 2 dominates the Status-quo for all metrics categories and implies 40% more carbon benefits and 60% more consumer surplus. This is stemming form different dwellings targeting strategies in each scenario. Project 2 targets all dwellings under D in the city while the status-quo is indifferent on the initial EPC band. This highlights the incremental gain from having specific policies prioritizing the most inefficient dwellings.

Table 5: Cost effectiveness of projects for carbon and consumers surplus

	CO2 (tons/1,000£)	**CO2 (tons/year.dwelling)**	**Consumer surplus (£/1,000£)**	**Consumer surplus (£/year.dwelling)**
Project_1	0,57	14.42	0.12	3.07
Project_2	2.13	5.60	0.81	2.12
Status-quo	1.69	3.24	0,59	1.14

4.4 Sensitivity Analysis (in progress)

This section is a work in progress. First, the sensitivity of the results to retail prices will be examined. We will see that the impacts of project 1 are very sensitive to the evolution of prices. The NPV of Project 1 decrease with heating price trends. Heat networks are attractive only when the prices of other energy sources increase significantly more than the price of the heat network and are high enough to generate large expenditures savings.

Second, the shortfall in heating savings will be investigated. We will study the differences when end-users fully invest in retrofitting measures. This provides an upper bound for the NPV of Project 2 and indicate the maximum potential impacts generated from energy efficiency retrofits.

Finally, an alternative scenario bundling heat networks and energy efficiency retrofits at the dwelling level will be studied. We will see that the interaction of the two projects improves both consumer surplus and carbon emissions as compared to original projects. Besides, the gains from the energy efficiency improvements offset the loss implied by the increase in energy price for the heating networks, removing the necessary trade-off between social and environmental benefits.

5 Discussion and conclusion

This paper conducts an ex-ante Cost-Benefit Analysis to assess which project in residential heating the Bristol City Council should adopt in order to cut carbon emissions and alleviate fuel poverty. The city has the choice between a district heating network or an energy efficiency retrofit program. A model is constructed to estimate the social costs and benefits of each project, evaluated against a status-quo scenario. We suggest that the district heating networks project should be adopted by the city, yielding a NPV more than ten times higher than energy efficiency retrofits. This result is sensitive to long-term retail energy price trends and the district heating network could generate more benefits for end-users as retail gas prices rise.

Through this assessment, the paper highlights several results. First, each project option is better at delivering one of the two objectives settled by the city. District heating networks generate more carbon savings and expenditure savings while the energy efficiency retrofits program is better to target low-income households and to deliver comfort gains. Besides, district heating networks have a negative effect on rental tenures, likely to pertain to lower income levels, by lowering their comfort. This highlights a necessary trade-off encountered by the city between cutting carbon emissions and improving its inhabitants well-being.

Second, energy efficiency retrofits are more cost-effective than district heating networks. They cut carbon emissions and deliver consumer surplus at a lower marginal cost. Conversely district heating networks are more efficient at delivering benefits per dwelling connected. This suggests that while energy efficiency retrofits should be implemented first under limited financial resources, district heating networks are required to decarbonize more deeply the building stock and get closer to the city's objectives.

Third, under-investments in energy efficiency retrofits from end-users are significant and imply an important shortfall in energy savings. This shortfall is detrimental to the profitability of energy efficency retrofits. The loss induced by under-investments in Project 2 is estimated at £2 million in net present value (provisional result).

Finally, bundling energy efficiency retrofits and district heating networks at the dwelling level would be the most attractive option. On the one hand, heat networks produce an important decrease in carbon emissions, on the other hand energy efficiency retrofits balance the loss in comfort implied by district heating networks. However there might be significant barriers to merge the two projects at the dwelling level: heating networks are less economically viable in low density districts and the two projects would require important works on existing buildings.

The model constructed in this paper is based on an open-access and standardized data-set and calibrated on academic literature. The paper intended to create a model that could be easily replicated to other case studies. This paper is a work in progress and several limits are identified. The heating demand function could be improved and adopt a non-linear shape to better model upper bounds. Rebound effects could also vary in time to account for long term effects in individuals demands. The calibration of the model could be refined as well. Only limited and simplified assumptions are done on energy prices trends and CO2 factors. Estimates of rebound effects and price elasticity are parameters that are still in calibration. The assessment could also be greatly improved by incorporating end-users' actual consumption data, allowing to produce more realistic heating demands and to estimate rebound effects and heating elasticities in-situ.

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6 Appendix

6.1 Appendix A: Reference trends

Table 6: Reference trends assumptions

Input	Value in 2021	Trend p.a.	Source
Electricity price	180 £ per MWh	+1% increase	EU commission 2019 (ec.europa); BEIS Quarterly Retail; SAP 2012 Prices (June, 2021)
Natural gas price	40 £ per MWh	+2% increase	EU commission 2019 (ec.europa); BEIS Quarterly Retail Prices; SAP 2012 (June, 2021)
Electricity gird carbon factor	0.266 kg per kWh	-0.8 % decrease	ADEME bilan ges database, 2021; BEIS, Government Greenhouse Gas Conversion Factors, 2021
Natural gas carbon factor	0.216 kg per KWh	-1% decrease	ADEME bilan ges database, 2021; BEIS, Government Greenhouse Gas Conversion Factors, 2021
Biomass carbon factor	0.030 kg per KWh	-	ADEME bilan ges database, 2021; BEIS, Government Greenhouse Gas Conversion Factors, 2021

6.2 Appendix B: Retrofitting cost matrix taken from Giraudet et al. (2021)

cost Â£ per m2	F	E	D	C	B	A
G	65,36	116,96	172,86	233,06	301,86	380,12
F		54,18	111,8	175,44	246,82	328,52
E			60,2	125,56	199,52	284,66
D				67,94	145,34	233,06
C					79,98	171,14
B						94,6

6.3 Appendix C: Literature review of eslaticity estimates

Table 7: Literature review of rebound effect estimates

Topic	Paper	Estimates	Methodology
Rebound effect	Aydin et al (2017)	0,199 – 0,485	Various econometric approaches on a sample of 563,000 households in the Netherlands
Rebound effect	Sorrell et al (2009)	0,32 – 0,5	Review of 20 papers studying rebound effect in residential heating
Rebound effect	McCoy et al (2021)		Various econometric approaches on a sample of 4 million households the UK
Rebound effect	Coyne et al (2018)	0.33 â 0.41	Quasi-experiment on a sample of 260 social housing tenures in Ireland
Rebound effect	Chitnis et al (2015)	0,41 (gas) – 0,48 (electricity)	Household demand model and inputâoutput model
Price elasticity	Chitnis et al (2015)	-0,09 (gas) – -0,07 (electricity)	Household demand model and inputâoutput model
Price elasticity	Lambarderia et al (2016)	-0,126 (electricity) – -0,180 (gas)	Meta-regression analysis on paper studying energy services price elasticity
Price elasticity	Sorrell et al (2009)	-0,1 – -0,58	Review of 20 papers studying rebound effect in residential heating
Temperature take-back	Sorrell et al (2009)	0,05 – 0,30	Review of 20 papers studying rebound effect in residential heating
Temperature take-back	Hamilton et al (2011)	0,06 – 0,2	Assessment of the Warm Front efficiency program on a sample of 1600 dwellings
Temperature take-back	Hedinger et al (2018)	0,110 – 0,144	Stated preferences approach on 3555 surveyed households in Switzerland
Temperature take-back	Greene et al (2015)	0,76°C (living room) – 2,82°C (bedrooms)	Assessment of the Warm Front efficiency program on a sample of 1600 dwellings (report)

6.4 Appendix D: Estimation of actual heating savings

Here the EPC data-set in extended to the whole Southwest region, where dwellings are identified at the LSOA level (1,558,777 observations). The data-set is reduced to dwellings that had conducted multiple EPCs through time. The data-set is then split into two groups: a control group comprises dwellings with multiple certificates that did not retrofitted and a treatment group with dwellings that did retrofit. Actual savings are computed for all dwellings and is the difference between standard consumption before and after over the standard consumption before. The potential heating savings is derived in the same way form the ex-ante potential heating consumption.

The model specification is as follow:

$$Y_{i,k,t} = \beta + \gamma X_{i,t} D_{i,t} + \theta Z_{i,t} + \lambda_t + \mu_k + \epsilon_{i,k,t} \tag{9}$$

Where $Y_{i,k,t}$ denotes for the actual heating savings achieved in dwelling i and location k at time t, $X_{i,t}$ is the potential heating savings estimated by the previous EPC for the dwelling and is interacted with $D_{i,t}$ a dummy variable equal to 1 if the dwelling implemented a retrofit between the two EPCs. $Z_{i,t}$ is a vector of characteristics at the dwelling level, λ_t and μ_k are year and location fixed effects. The results are outlined in the table bellow.

Here right some results and interpretaiton stuff. Say for one group, for the other, after EE and interaction look at year dummy with significant effects and say that this is due to price, look at total floor area go deeper in measres before after in the EPC

Table 8: Regression results

	Dependent variable:
	Act.Heat_sav
Pot.Heat_sav	0.159^{***}
	(0.023)
EE_upgrade	0.406^{***}
	(0.009)
Total_floor	-0.00003
	(0.0001)
Tenurerental (private)	0.022^{***}
	(0.007)
Tenurerental (social)	-0.073^{***}
	(0.006)
Diff_time	-0.044^{***}
	(0.001)
Pot.Heat_sav:EE_upgrade	0.114^{***}
	(0.028)
Constant	-0.387^{***}
	(0.064)
Observations	15,918
R^2	0.502
Adjusted R^2	0.497
Residual Std. Error	0.292 (df = 15768)
F Statistic	106.526^{***} (df = 149; 15768)
Note:	$^{*}p<0.1$; $^{**}p<0.05$; $^{***}p<0.01$

6.5 Appendix E: Summary statistics of the regression data-set

Table 9: Summary statistics

Statistic	N	Mean	St. Dev.	Min	Pctl(25)	Pctl(75)	Max
Conso_before	15,918	934.005	616.472	177	549	1,112	7,142
Conso_potential	15,918	588.097	330.974	92	400	674	6,575
Conso_after	15,918	887.285	558.946	173	549	1,046	6,746
Rebound	15,918	0.394	3.662	−75	0	0.6	191
Building_ref_number	15,918	5,039,199,036.000	2,883,912,719.000	289,078	2,553,820,768	7,540,719,303	9,999,860,568
Total_floor	15,918	81.790	42.038	15.980	55.278	93.000	443.000
Heated_rooms	15,918	3.835	1.791	0	3	5	34
Year1	15,918	2,013.454	2.845	2,004	2,012	2,015	2,020
Year2	15,918	2,015.360	2.743	2,008	2,014	2,018	2,020
Current_efficiency	15,918	55.797	16.842	1	47	68	138
EE_upgrade	15,918	0.625	0.484	0	0	1	1
TIME_LAPS	15,918	0.376	0.484	0	0	1	1

7 Appendix F: Summmary statistics per tenures

Table 10: Rental (social)

Statistic	N	Mean	St. Dev.	Min	Max
Energy efficiency	16,665	67.241	11.110	1	97
Expenditures	16,665	529.958	243.489	2.983	4,418.531
Part gas	16,665	0.762	0.426	0	1
Floor area	16,665	62.013	22.374	11.000	945.400

Table 11: rental (private)

Statistic	N	Mean	St. Dev.	Min	Max
Energy efficiency	34,508	63.430	12.266	1	102
Expenditures	34,508	693.831	360.700	3.026	8,017.892
Part gas	34,508	0.755	0.430	0	1
Floor area	34,508	73.339	38.852	3	1,690

Table 12: owner-occupied

Statistic	N	Mean	St. Dev.	Min	Max
Energy efficiency	60,495	61.167	12.312	1	107
Expenditures	60,495	822.908	413.490	1.272	13,023.080
Part gas	60,495	0.885	0.319	0	1
Floor area	60,495	93.560	45.787	7	3,039

Table 13: Unknown

Statistic	N	Mean	St. Dev.	Min	Max
CURRENT_ENERGY_EFFICIENCY	16,114	75.773	11.933	4	142
RealExp_hat	16,114	487.932	296.053	0.103	4,338.185
IS.GAS	16,114	0.624	0.484	0	1
TOTAL_FLOOR_AREA	16,114	72.342	35.445	1.350	624.000

8 Appendix F: Tenures x central districts appartments

Table 14: owner-occupied

Statistic	N	Mean	St. Dev.	Min	Max
CURRENT_ENERGY_EFFICIENCY	6,766	67.619	13.930	1	99
RealExp_hat	6,766	592.193	327.543	1.272	5,932.502
IS.GAS	6,766	0.570	0.495	0	1
TOTAL_FLOOR_AREA	6,766	63.153	26.248	10	309

Table 15: rental (social)

Statistic	N	Mean	St. Dev.	Min	Max
CURRENT_ENERGY_EFFICIENCY	4,080	68.925	10.309	12	89
RealExp_hat	4,080	471.379	218.869	2.983	4,355.034
IS.GAS	4,080	0.611	0.488	0	1
TOTAL_FLOOR_AREA	4,080	50.427	16.887	11	618

Table 16: rental (private)

Statistic	N	Mean	St. Dev.	Min	Max
CURRENT_ENERGY_EFFICIENCY	11,802	65.845	13.110	1	99
RealExp_hat	11,802	576.064	292.540	3.026	4,027.034
IS.GAS	11,802	0.563	0.496	0	1
TOTAL_FLOOR_AREA	11,802	56.884	25.391	8	308

Table 17: Unknown

Statistic	N	Mean	St. Dev.	Min	Max
CURRENT_ENERGY_EFFICIENCY	6,410	76.080	10.554	18	109
RealExp_hat	6,410	444.457	240.004	0.103	2,087.091
IS.GAS	6,410	0.350	0.477	0	1
TOTAL_FLOOR_AREA	6,410	57.243	24.255	2.090	228.600

9 Appendix F: Tenures x low efficient dwellings to retrofit

Table 18: Owner-occupied

Statistic	N	Mean	St. Dev.	Min	Max
CURRENT_ENERGY_EFFICIENCY	13,788	45.168	8.882	1	54
RealExp_hat	13,788	1,131.760	452.065	289.086	7,658.162
IS.GAS	13,788	0.841	0.365	0	1
TOTAL_FLOOR_AREA	13,788	106.670	51.407	7	973

Table 19: Rental (social)

Statistic	N	Mean	St. Dev.	Min	Max
CURRENT_ENERGY_EFFICIENCY	1,955	44.742	9.955	1	54
RealExp_hat	1,955	850.594	272.486	190.714	4,418.531
IS.GAS	1,955	0.402	0.490	0	1
TOTAL_FLOOR_AREA	1,955	66.781	24.191	14	415

Table 20: rental (private)

Statistic	N	Mean	St. Dev.	Min	Max
CURRENT_ENERGY_EFFICIENCY	6,342	45.275	9.192	1	54
RealExp_hat	6,342	1,005.643	398.778	250.575	7,471.930
IS.GAS	6,342	0.602	0.490	0	1
TOTAL_FLOOR_AREA	6,342	81.006	43.491	10	634

Table 21: Unknown

Statistic	N	Mean	St. Dev.	Min	Max
CURRENT_ENERGY_EFFICIENCY	753	44.450	8.675	4	54
RealExp_hat	753	1,048.400	409.283	308.144	4,286.209
IS.GAS	753	0.615	0.487	0	1
TOTAL_FLOOR_AREA	753	91.765	45.827	10	355