ISEC 2024 – 3rd International Sustainable Energy Conference
Policies for Phase-Out Fossil Fuels and Carbon Management
https://doi.org/10.52825/isec.v1i.1161

Published: 26 Apr. 2024

Agent-Based Modelling of Policy Interventions on District Heating Adoption

Thomas Cowley[1], Timothy Hutty[1], and Solomon Brown[1]

[1] University of Sheffield, UK

*Correspondence: Thomas Cowley, tcowley1@sheffield.ac.uk

Abstract. This study employs an agent-based model to examine the adoption of District Heating Networks (DHNs) in heat zoning areas, focusing on the impact of three policy interventions, subsidy, tax and mandating connections. Analysing a case in South Yorkshire, UK, the research highlights a notable synergy in policies, with a combined £25.5 million from subsidies and tax incentives leading to a 28% (£33 million) reduction in infrastructure costs. The policies accelerated the DHN connection rate, achieving full coverage by 2028, two years ahead of the baseline scenario. Investment costs per household were significantly reduced from £2000 to £1460, aligning with governmental cost projections. The study acknowledges optimistic connection rates and suggests future work to include realistic project timelines and incorporate social and behavioural factors in DHN adoption. The findings show the effectiveness of integrated policy frameworks in promoting DHNs.

Keywords: Agent-Based Modelling, Policy Analysis, District Heating Adoption

1. Introduction

The global push towards renewable and low-carbon energy solutions has been amplified by key international agreements, notably the 2016 Paris Agreement. In alignment with its commitments, the United Kingdom has an ambitious plan to achieve net-zero emissions by 2050, as outlined in the Sixth Carbon Budget [1]. Heating and cooling accounts for a substantial portion of the UK's energy consumption and emissions, therefore a strategic shift in this sector is important [2]. In response, district heating networks (DHNs) offer a promising solution. These systems utilise centralised energy generation to distribute heat via insulated piping, ideal for densely populated or designated heat zoning areas [6]. The flexibility of district heating (DH) systems to harness a variety of energy sources, from industrial by-products and localised low-carbon energy sources, makes them a great technology for reducing reliance on natural gas, cutting carbon emissions, and potentially reducing household fuel bills by up to 30% [6]. Yet, widespread DH implementation has challenges, such as securing reliable heat sources, attracting investment, and ensuring sufficient user demand for profitability. Policymaking plays a critical role in this context. Subsidies and other interventions are essential to motivate the expansion of DH networks, but the decision ultimately rests with property owners, who must weigh the cost of retrofitting against the backdrop of economic conditions [7], [8].

As the drive for net-zero gains momentum, there is a focus on understanding the uptake of low-carbon solutions and the effects of policy interventions [9], [10], [11]. Agent-Based Modelling (ABM) has proven to be a particularly effective tool for simulating these dynamics, capturing the intricate decision-making behaviours of individuals and organisations within DH networks [7], [8], [12], [13]. This study advances the field by applying an ABM approach to explore the adoption of DH networks, focusing on the role of policy interventions. It builds upon the foundational work of Busch et al. (2016) [14], which underscores the significance of actor collaboration in the development of DHNs, and Pagani et al. [15], who detail the agent characteristics and logistical considerations within an existing network extension. Moreover, the model considers the control and monitoring aspects of DH systems as discussed by Wernstedt and Davidsson [16], and the group decision-making processes in heat transitions explored by Nava-Guerrero et al. [17], which are needed to understand the dynamics of DHN expansion. These pieces of literature make up the bulk of current research surrounding DHN uptake, thus creating simple but effective models that build upon this is enough to take the field a step further.

Considering these contributions, this research employs an agent-based model to simulate the interactions and decision-making processes among stakeholders such as district heating providers, local governments and network users. The model aims to simulate the growth rate and the impact of various policy scenarios on the adoption and infrastructural investment in DH networks. By integrating the key insights from the literature, using open-source data such as census data this study not only explores the potential of DHNs to meet current and future heating demands but also assesses the efficacy of different policy measures designed to accelerate their uptake. South Yorkshire, UK, presents a unique context for this study, given its varied urban landscapes, economic reliance on both traditional industries and emerging technologies, and diverse social characteristics. These factors contribute to distinct challenges and opportunities in adopting DHNs making it a representative case for examining policy impacts. Thus, the present study positions itself between policy, technology, and market dynamics and contributes to the literature by providing evidence on the effectiveness of policy interventions within the UK's ambitious net-zero framework.

2. Methodology

2.1 Overview of agent-based model design

This section describes the development of an ABM to simulate district heating dynamics in the UK, specifically in government-designated heat zoning areas [18]. The model, implemented in AnyLogic simulation software [19], incorporates economic, climatic, and socio-political factors, simulating interactions among key entities: infrastructure, district heat network providers (DHP), households, and local government. The model's calibration allows for the testing of various policy interventions. The full functionality of the model is currently a work in progress, thus the red circles in Figure 1 (flow diagram of full agent-based adoption model) indicate what inputs and model blocks are currently being used for this work.

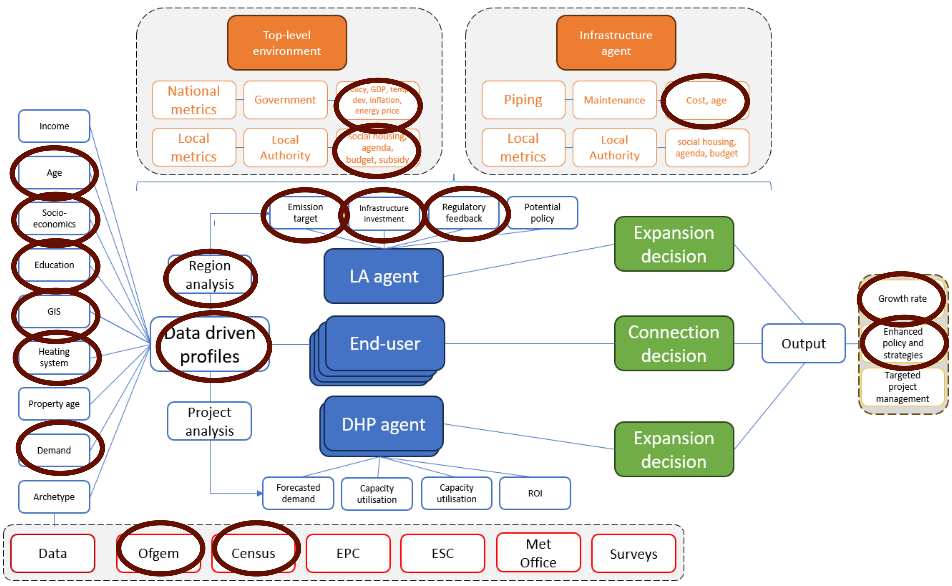

Figure 1. *Flow diagram of agent-based adoption model; red circles represent current functionality used for this case study*

2.2 Defining Output Areas

Output areas are fundamental units in this model, defined based on census data [20]. Each output area represents a group of 100-400 houses, encompassing comprehensive demographic and socioeconomic characteristics. These areas are geographically delineated and integrated into the model with geographic information system (GIS) locations and boundaries allowing for spatial modelling. This granular approach allows for the creation of detailed profiles for each area within the zoning area. The classification logic applied to determine the socioeconomic grade and profile of individuals within an output area considers characteristics such as their tenure status and occupation type. This classification is crucial for understanding the sociodemographic composition of the population, which in turn informs the potential adoption rates of district heating networks.

Individuals in social rented housing, rented from social landlords or local authorities, fall under social grade DE, representing lower occupational and socioeconomic status. High-level managerial and professional individuals are classified as social grade AB, while those in administrative and secretarial roles owning their homes are categorized as C1. Those not owning homes fall under C2, representing skilled manual occupations. The educational level determines the classification for those in service, sales, and operational roles, with those lacking higher qualifications placed in DE. The model employs this classification system to affect the decision-making in district heating adoption, factoring in the socioeconomic status of households in various output areas. Figure 2 shows all the output areas in South Yorkshire, UK, each a differing colour and with black boundaries.

Weightings and calibrations are derived from Ofgem survey data via a simple regression [21]. Social grade significantly influences the adoption of DHNs through its impact on the scoring system that calculates the probability of connection. Higher social grades, typically associated with property ownership and modern heating systems, are likely to achieve higher scores, reflecting a greater likelihood of adopting DHN. In contrast, lower social grades, often linked with social rented housing and less efficient heating systems, tend to score lower. This difference in scoring, coupled with variations in economic activity related to social grade, heating system, property type and age cumulatively feeds into a logistic function. This function ultimately determines the likelihood of a household's connection to DHN, with higher overall scores suggesting a greater chance for connection.

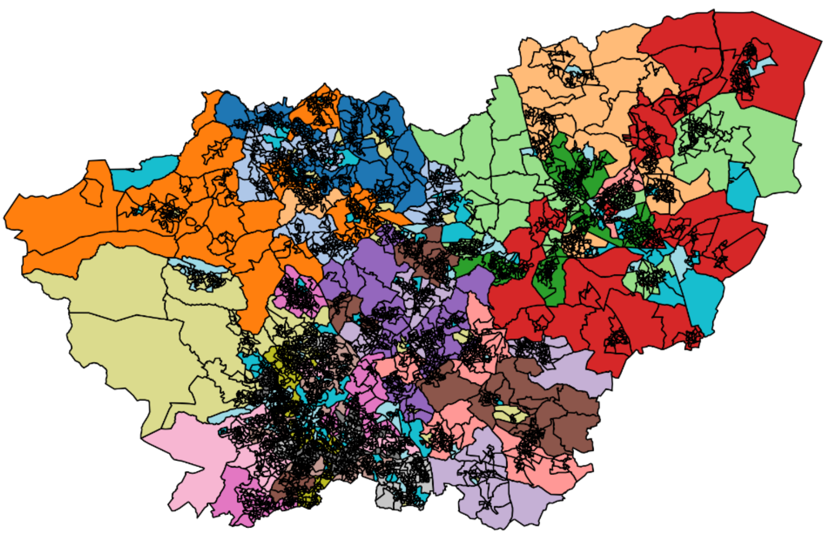

Figure 2. *Output area and boundaries in South Yorkshire, UK.*

2.3 Main environment (global agent)

Equation 1 calculates the economic impact factor at time t, using a sensitivity weight λ to evaluate the deviation of current gross domestic product (GDP) from its average value, serving as a baseline for economic comparison of the norm. The weighting allows adjustment to an output area to reflect economic resilience and susceptibility to macroeconomic trends.

$$E_t(t) = \lambda_i \cdot \left(GDP(t) - GDP_{avg}\right) \tag{1}$$

Where $GDP(t)$ represents the current Gross Domestic Product at time t, GDP_{avg} is the average GDP.

Equation 2 assesses the impact of climate change by multiplying the temperature deviation at time t with a sensitivity factor. Again the sensitivity factor can be varied in output areas to reflect the pressure of net-zero targets on the population.

$$C_t(t) = \psi_i \cdot D_t(t) \tag{2}$$

Where $D_t(t)$ is the deviation from the average global temperature at time t.

2.4 Piping agent

Equation 3 calculates the installation cost and accounts for the basic installation expenses, adjusted for the density of connections (indicative of how many households/buildings are to be connected) and the complexity of the installation which can be adjusted for any infrastructure challenges.

$$I_c(t) = PI_c \cdot (1 + \varphi \cdot HD_i) \cdot IC_i \tag{3}$$

Where PI_c is the installation base cost, HD is the household density and IC is a complexity factor.

Both PM_c and PI_c are derived from a combination of factors including material and labour costs, and can be adjusted using the global variable $E_t(t)$.

2.5 DHP Agent

Equation 4 calculates the total demand based on connected output areas and their connected percentage. Equation 5 calculates the heat price.

$$Demand_i(t) = \sum(OA_i \cdot CP_i \cdot HeatPrice(t)) \tag{4}$$

$$HeatPrice(t) = BasePrice \cdot (1 + MarketFactor(t) + PolicyFactor(t)) \tag{5}$$

Where OA_i is the ith output area, and CP_i is the associated connection percentage, $HeatPrice(t)$ is the dynamic heat price per kWh at time t, which varies based on market conditions, subsidies, and carbon pricing mechanism.

Equation 6 calculates revenue from demand and heat price per kWh.

$$Revenue(t) = HeatPrice(t) \cdot Demand(t) \tag{6}$$

2.6 Output Area

Equation 7 determines the cost of expanding the DHN based on demographic factors of the output area. In densely populated areas, the complexity and logistical challenges of installing or expanding a DHN can increase.

$$ExpansionCost_i(t) = EC_{base_i} \cdot (1 - G_f) \cdot (1 + a \cdot HD_i \cdot (1 - \beta \cdot SHProp_i) \quad (7)$$

Where G_f is a government grant factor reducing the base expansion cost and represents the influence of grants due to zoning laws, EC_{base} is the initial expansion cost calculated from output area parameters. $SHProp$ is the proportion of social housing in the output area.

2.7 House Agent

The probability of a household deciding to connect to the DHN is calculated using a logistic function, as shown in Equation 8. This probability is determined by the cumulative score (Z), which is derived from various weighted factors, as illustrated in Equation 9. Each of these scores is weighted by their respective β coefficients, which quantify their relative importance in the model.

$$P(Connect) = \frac{1}{1+e^{-Z}} \quad (8)$$

$$Z = \begin{matrix} \beta_0 + \beta_1 \cdot propertyType + \beta_2 \cdot heatingSystem + \beta_3 \cdot economicActivity + \beta_4 \\ \cdot AgeGroup(t) + \beta_6 \cdot SocialGrade + \beta_7 \cdot PolicyAdjustment(t) + \beta_8 \cdot SubsidyLevel(t) \\ +\beta_9 \cdot Heat\ Price(t) \end{matrix} \quad (9)$$

Where $propertyType$ is influenced by the type of property, where different property types are assigned specific scores. $heatingSystem$ reflects the current heating system in use, with different systems being scored differently based on their efficiency and type. $economicActivity$ accounts for the economic activity of the household, with different employment statuses leading to varied scores. $PolicyAdjustment$ and $subsidyLevel$ are parameters that can affect the outcome of the logistical function and can be changed to enact policies.

2.8 Local Government

Equation 10 assesses the gap between targeted and current emissions.

$$EmissionGap(t) = TE - CE(t) \quad (20)$$

Where TE is the target emissions and CE is the current emissions.

Equation 11 determines the investment in infrastructure based on budget and stakeholder pressure. This equation estimates the investment in infrastructure based on a policy strength parameter, which represents the local government's commitment to DHN expansion, and the difference between required and current infrastructure.

$$II(t) = \theta \cdot PS \cdot (RI(t) - CI(t)) \quad (31)$$

Where θ is a coefficient representing the efficiency of budget utilisation. PS is the policy sensitivity that reflects the intensity of local government policies and stakeholder pressure. RI and CI represent the infrastructure needs and current state, respectively.

Equation 12 calculates the infrastructure needed to meet the total demand for district heating in the output area. It multiplies the total demand at time t by the amount of infrastructure required per unit of demand.

$$RI(t) = TotalDemand(t) \cdot InfrastucutreCostPerUnitDemand \quad (42)$$

$TotalDemand$ is the total heating demand in the output area at time t, $InfrastucutreCostPerUnitDemand$ is an estimated value representing the amount of infrastructure (e.g., piping, pumps) needed per unit of heating demand.

2.9 Feedback Mechanisms and Behavioural Rules

This adoption-infrastructure investment feedback loop, described by Equation 13 is modelled to reflect the dynamic interplay between DHN adoption and infrastructure investment.

$$II(t) = \theta \cdot DHNadoption(t) \cdot InvestmenMultipler \quad (13)$$

Where $DHNadoption(t)$ is the percentage of total households connected to the DHN at time t, θ is the scaling factor that translates adoption to investment needs, $InvestmenMultipler$ reflects the proportionality between current adoption levels and required infrastructure investment.

This market dynamics-policy feedback loop described by Equation 14 affects how market dynamics influence policy decisions which in turn affects market conditions

$$PolicyAdjustment(t) = \theta \cdot MarketCondition(t) \cdot PS \cdot EnvFactor(t) \quad (14)$$

Where $MarketCondition(t)$ is the average DHN cost of heat at time t, and PS is the policy sensitivity and affects how responsive policies are to changing market conditions. $EnvFactor(t)$ reflects the environmental policy impact.

3. Case study

The following case study, centred on simulating the adoption of DHNs in South Yorkshire, UK, was calibrated with key parameters mirroring real-world conditions and policy impacts, as derived from government 'heat networks' documentation and study [22]. In the base case scenario, which represents the status quo without policy interventions, the parameters were set to reflect the following specific values, shown in Table 1.

Table 1. *Baseline parameters*

Parameter	Value
Economic Impact Factor (λ)	0.5
GDP Current Value ($GDP(t)$)	Based on the latest UK GDP data [23]
Average GDP (GDP_{avg})	Based on average UK GDP data [23]
Climate Change Sensitivity Factor (ψ)	0.3
Installation Base Cost (PI_c)	£800 [22]
Connection Density Adjustment (φ)	Adjusted based on the output area
Complexity Factor (I_c)	Adjusted based on project complexity of output area
Base Price for Heat Price	Current market rate [22]
Market Factor for Heat Price	Neutral in the base scenario
Policy Factor for Heat Price	Neutral in the base scenario
Initial Expansion Cost (EC_{base_i})	[22]
Proportion of Social Housing ($SHProp$)	Census data [20]
Household Decision-making Coefficients ($\beta 0\ to\ \beta 9$)	calculated from Ofgem regression [21]
Target Emissions (TE)	UK's target emissions for 2050 [22]

Current Emissions (CE)	Model calculated
Infrastructure Cost per Unit Demand	Model calculated
Average Household Demand per year	12.3MWh [22]

In assessing the potential impacts of various policy interventions on the adoption of DHNs, three distinct policies were simulated within the agent-based model tailored for South Yorkshire, UK. Each policy, slated for implementation at different times over a decade, is designed to target specific barriers to DHN expansion and uptake.

- **Policy A** introduces a subsidy increase in 2023, intending to lower the financial barriers to installation. By reducing the base cost of installation and amplifying government grants, this policy seeks to alleviate the upfront financial burden on households and DHN providers, thereby fostering a more rapid expansion of the network. To apply this a decrease to the Installation Base Cost (PI_c) by 20% to reflect the reduced installation cost. Increase the Government Grant Factor (G_f) by 20% to simulate the enhanced governmental support.

- **Policy B**, set for 2026, leverages tax incentives to influence market behaviours. By adjusting the policy factor, this intervention aims to make sustainable heating options more economically attractive, promoting a shift towards greener energy sources. To apply this the Policy Factor ($PolicyFactor$) was modified by 10%, reflecting the tax on heat price and its influence on the market.

- **Policy C** will enact a mandatory adoption strategy for social housing by 2028. With a substantial increase in connection rates and a local authority subsidy, this policy addresses the socio-economic factors influencing energy choices in social housing, ensuring that these communities are not left behind in the transition to sustainable heating solutions. For the output areas predominantly comprising social housing (as indicated by the $SHProp$ parameter), increase the Connection Percentage (CP_i) by 30% to simulate the mandatory adoption. Additionally, introduce a 20% subsidy from the local authority by adjusting the Local Government Policy Sensitivity (PS) and/or the Subsidy Level ($\beta 8$) in the logistic function for these specific areas.

4. Results

This section presents the outcomes from the 10-year agent-based simulation within a designated heat zoning area of South Yorkshire, UK. The simulation, covering 493 output areas housing 58,053 dwellings, provides a nuanced picture of DHN adoption trends and the infrastructure investment landscape under a range of policy scenarios. Incorporating economic, climatic, and socio-political variables. The accompanying figures detail the adoption growth trajectory of DHNs alongside the progression of cumulative investments throughout the simulated period. In the base scenario, by 2030, the average cost of district heating per household is projected at £165 per MWh or 2030£ per household, aligning closely with government documentation [22] that cites a range of £80 to £161 per MWh. Under policy-influenced scenarios, a less substantial investment is noted, averaging £1460 per household and £119 per MWh, indicative of the impact of subsidies, tax incentives, and mandated adoptions on market dynamics.

The simulation over 10 years revealed that policy scenarios culminated in a £33 million reduction in investment, equating to a notable 27.97% decrease compared to the base case. This aligns with a projected £17 million subsidy increase and an £8.5 million tax incentive, contributing to this cost-effectiveness. Additionally, the mandatory adoption policy in social housing is estimated to connect an extra 17,416 houses to the DHN. Although the 28% reduction in required investment suggests a synergistic effect of the combined policies, which surpasses the sum of their individual impacts. The policies' interplay appears to enhance the financial and operational viability of the DHNs, advocating for a multi-faceted policy framework. The adoption rate reaches near saturation, with a 100% connection in the base case by 2030, whereas policy interventions reduce this to 2028. The following Figures illustrate the growth rate of the district heating network adoption and the investment trends over the simulation period.

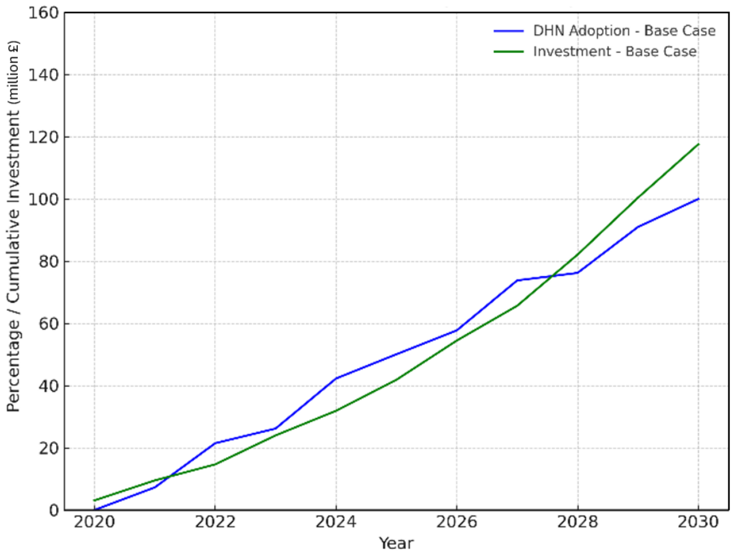

Figure 3. *Trajectory of District Heating Network (DHN) Adoption and Cumulative Investment in South Yorkshire, UK*

Figure 3 shows the baseline scenario for DHN adoption in South Yorkshire, UK, without policy intervention. It tracks the percentage of DHN adoption and cumulative infrastructure investment from 2020 to 2030. The gradual increase in adoption (blue line) and steady rise in investment (green line) reflect organic market growth driven by individual user decisions and market conditions.

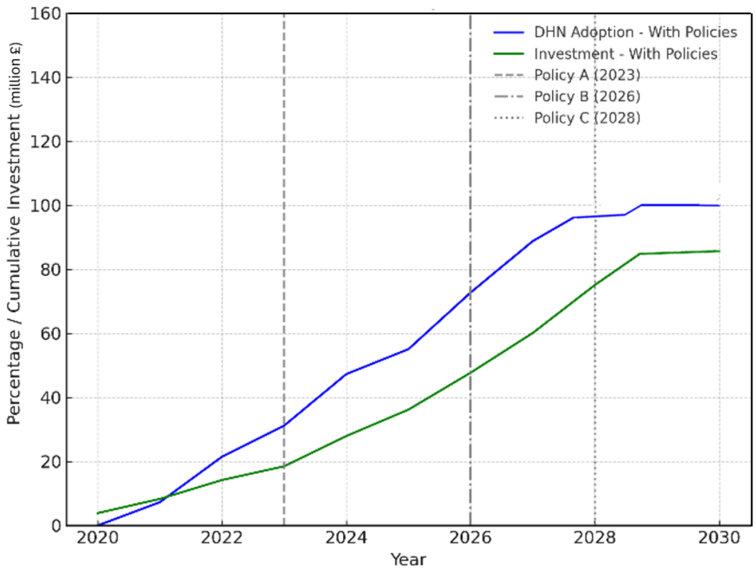

Figure 4. *Impact of Policy Interventions on DHN Adoption and Cumulative Investment in South Yorkshire, UK*

Figure 4 depicts the impact of policy interventions on DHN adoption and investment. Policy A, introduced in 2023, significantly increases DHN adoption, as shown by the rising blue line, demonstrating its effectiveness in encouraging user connections. The green line, representing investment, shows a plateau, suggesting cost alleviation by the government grant policy. With Policy C in 2028, there's a sharp increase in DHN adoption, especially in social housing, albeit with a slight initial lag. This figure highlights the accelerated transition to sustainable heating due to these policies. Post-2023, the adoption and investment trajectories in the policy scenario show marked deviation from the base case, indicating the success of the policies in driving DHN expansion. The adoption rates continue to climb, even after Policy C in 2028, though the impact here is less pronounced than earlier policies, hinting at nearing saturation.

This comparison between Figures 3 and 4 underscores the significant influence of government policies on expediting the transition to sustainable heating solutions. The period from 2020 to 2023 serves as a baseline, with both scenarios beginning similarly, crucial for evaluating the effect of subsequent policy interventions. Post-2023, with Policy A's implementation, a notable change in DHN adoption and investment trends is observed, indicating the policy's effectiveness in boosting DHN expansion. This is evidenced by differences from the base scenario, highlighting Policy A's role in reducing financial barriers to infrastructure development. The introduction of Policy B in 2026 further accelerates DHN adoption, as shown by the steepening trend in the policy-inclusive scenario. This demonstrates Policy B's efficacy in maintaining the growth momentum, with investment trends mirroring this positive trajectory. Finally, Policy C in 2028 introduces a shift in investment dynamics, indicated by a brief plateau and subsequent rise in adoption rates. Although the impact here is more subdued, it points to the nearing of market saturation and the challenges of connecting the remaining households. It is unknown why there is a large spike just before the simulation ends perhaps the effect of mandatory connectivity kicking in.

5. Discussion

The 10-year simulation for South Yorkshire's heat zoning area underscores the critical role of policy interventions in steering the adoption of DHNs and optimising infrastructure investments. Quantitative analysis reveals a notable cost reduction in the policy scenario, with an average district heating cost per household decreasing to £1460, translating to £119 per MWh by 2030—a 27.97% decrease compared to the base case. This aligns closely with government studies [22], suggesting an expected cost range for DHN heat of £80 to £161 per MWh.

The fiscal impact of policy measures is substantial, with a £33 million reduction in investment required, surpassing the sum of individual policy contributions (£25.5 million), and illustrating the synergistic potential of integrated policy frameworks. The adoption rates are projected to reach near-complete coverage earlier in the policy scenario by 2028, compared to 2030 in the base case, signifying a significant acceleration due to policy influences.

However, the projected timescales for DHN adoption, while encouraging, may be overly optimistic. Real-world complexities such as logistical challenges, stakeholder negotiations, and technological integration could extend these timelines. The simulation also suggests a plateau in investment following the introduction of Policy C in 2028, hinting at the approach toward a saturation point, where the remaining non-connected households may present unique challenges.

6. Conclusion

In conclusion, this research offers valuable insights into the dynamics of DHN adoption, particularly under the influence of multifaceted policy interventions. The study demonstrates the significant impact of integrated policy frameworks, combining subsidies, tax incentives, and mandatory connections, in accelerating the adoption process. Notably, the analysis revealed a synergistic effect of these policies, yielding a greater reduction in infrastructure investment costs than the sum of the individual policy costs. This underscores the benefits of a multi-faceted policy approach in driving efficient and sustainable DHN expansion and provides a roadmap for municipalities and policymakers. Specifically, the findings can inform strategic planning and policy formulation aimed at achieving net-zero targets in urban heating systems.

The simulation results indicate an improved growth rate, achieving a 100% connection rate by 2028, two years ahead of the baseline scenario. This faster adoption aligns with the UK's ambitious targets for sustainable energy and highlights the effectiveness of targeted policy measures. Additionally, the investment per household was significantly reduced under the policy scenarios, aligning with government estimates, and reinforcing the economic viability of these interventions.

However, the study also acknowledges certain limitations, such as the overly optimistic connection rates, suggesting the need for more realistic project timelines and considerations of retrofit turnaround times in future research. Moreover, the importance of integrating social and behavioural aspects into the model is emphasised, as these factors are crucial for a comprehensive understanding of DHN adoption dynamics. The findings pave the way for future work that incorporates these elements, thereby refining the accuracy and applicability of the model in real-world scenarios.

Data availability statement

The data supporting the findings of this study are openly available in public domain repositories, which means that other researchers have full access to the data sets that were utilized. The data sets are accessible via their respective public platforms and repositories, ensuring adherence to the principles of Findability, Accessibility, Interoperability, and Reusability (FAIR).

Author contributions

This research was guided by CRediT principles to recognize each author's specific roles. Thomas Cowley led the study, overseeing its conception, design, data collection, analysis, and manuscript drafting. Timothy Hutty contributed significantly to the conceptualization and model development, offering methodological guidance and data interpretation assistance. Solomon Brown, as the PhD supervisor, directed the research's overall trajectory and provided crucial insights into the research design and interpretation of results.

Competing interests

The authors declare that they have no competing interests.

References

[1] Committee on Climate Change, “The Sixth Carbon Budget,” 2020. [Online] Available: www.theccc.org.uk/publications.
[2] Frontier Economics, “Agent based modelling of a heat market,” 2021.
[3] D. Gadenne, B. Sharma, D. Kerr, and T. Smith, “The influence of consumers’ environmental beliefs and attitudes on energy saving behaviours,” Energy Policy, vol. 39, no. 12, pp. 7684–7694, Dec. 2011, doi: https://doi.org/10.1016/j.enpol.2011.09.002.
[4] S. Hall, “World Economic Forum,” 2022.
[5] International Energy Association, “World Energy Investment,” Paris, France, 2022.
[6] Energy Saving Trust, “What is District Heating?” 2018. [Online] Available: https://energysavingtrust.org.uk/what-district-heating/.

[7] J. Busch, C. S. E. Bale, C. Knoeri, and K. Roelich, “Emergence of District-Heating Networks; Barriers and Enablers in the Development Process,” 2014.
[8] M. Dowson, “Connecting Existing Buildings to District Heating Networks,” 2016.
[9] P. Vuthi, I. Peters, and J. Sudeikat, “Agent-based modeling (ABM) for urban neighborhood energy systems: literature review and proposal for an all integrative ABM approach,” Energy Informatics, vol. 5, 2022.
[10] L. M. H. Hall and A. R. Buckley, “A review of energy systems models in the UK: Prevalent usage and categorisation,” Appl Energy, vol. 169, pp. 607–628, 2016, doi: https://doi.org/10.1016/j.apenergy.2016.02.026.
[11] L. X. W. Hesselink and E. J. L. Chappin, “Adoption of energy efficient technologies by households – Barriers, policies and agent-based modelling studies,” Renewable and Sustainable Energy Reviews, vol. 99, pp. 29–41, 2019, doi: https://doi.org/10.1016/j.rser.2018.09.023.
[12] J. Webb, “Improvising innovation in UK urban district heating: The convergence of social and environmental agendas in Aberdeen,” Energy Policy, vol. 78, pp. 265–272, 2015, doi: https://doi.org/10.1016/j.enpol.2014.12.003.
[13] B. Talebi, P. A. Mirzaei, A. Bastani, and F. Haghighat, “A Review of District Heating Systems: Modeling and Optimization,” Frontiers in Built Environment, vol. 2, Oct. 2016, doi: https://doi.org/10.3389/fbuil.2016.00022.
[14] J. Busch, K. Roelich, C. S. E. Bale, and C. Knoeri, “Scaling up local energy infrastructure; An agent-based model of the emergence of district heating networks,” Energy Policy, vol. 98, pp. 66–75, Oct. 2016, doi: https://doi.org/10.1016/j.enpol.2016.08.028.
[15] M. Pagani, P. Maire, W. Korosec, N. Chokani, and R. S. Abhari, “District heat network extension to decarbonise building stock: A bottom-up agent-based approach,” Applied Energy, vol. 269, May 2020, doi: https://doi.org/10.1016/j.apenergy.2020.115021.
[16] F. Wernstedt and P. Davidsson, “An Agent-Based Approach to Monitoring and Control of District Heating Systems,” in Agent Technologies, Infrastructures, Tools, and Applications for E-Services, Berlin, Heidelberg, 2002, pp. 144–157.
[17] G.-del-Carmen Nava-Guerrero, H. H. Hansen, G. Korevaar, and Z. Lukszo, “The effect of group decisions in heat transitions: An agent-based approach,” Energy Policy, vol. 152, Apr. 2021, doi: https://doi.org/10.1016/j.enpol.2021.112149.
[18] Department for Business, Energy & Industrial Strategy, "Heat Network Zoning," UK Government, [Online]. Available: https://www.gov.uk/government/collections/heat-network-zoning. [Accessed 07.01.2024].
[19] T. A. Company, “No Title.” 2019, [Online]. Available: https://www.anylogic.com.
[20] Office for National Statistics, "Census 2021 Tables and Supporting Information," UK Government, [Online]. Available: https://www.nomisweb.co.uk/sources/census_2021_ts. [Accessed 05.01.2024].
[21] Office of Gas and Electricity Markets (Ofgem), "Ofgem Consumer Survey 2020 - Decarbonisation Insights," UK Government, [Online]. Available: https://www.ofgem.gov.uk/publications/ofgem-consumer-survey-2020-decarbonisation-insights. [Accessed 08.01.2024].
[22] Department for Business, Energy & Industrial Strategy, "Heat Networks," UK Government, [Online]. Available: https://assets.publishing.service.gov.uk/media/5a802b44e5274a2e8ab4e95d/heat_networks.pdf. [05.01.2024].
[23] Office for National Statistics. "Gross Domestic Product (GDP)." [Online]. Available: https://www.ons.gov.uk/economy/grossdomesticproductgdp. [Accessed: 10.01.2024].