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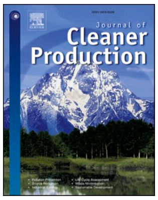

A novel temporal mixed-integer market penetration model for cost-effective uptake of electric boilers in the UK chemical industry

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ABSTRACT

The UK chemical industry is the largest consumer of natural gas for process heating and power generation, with an annual consumption of 26.3 TWh. Reduction in natural gas consumption and associated carbon emissions can be achieved through electrification of heat. However, the adoption of electric boilers is lethargic due to economic barriers. Hence, market-based policy interventions are required. This study aims to accelerate the adoption of electric boilers in the UK's chemical industry, aligning with the UK's ambitious 2035 industrial decarbonisation goals while considering economic impacts, by designing market-based policy interventions and comparing two adoption patterns. A novel multi-period Mixed-Integer Market Penetration Optimisation Model is developed and applied to inform decisions about transitioning from natural gas to electric boilers. The model is applied to a case study of all the heating systems (490 boilers) in the UK chemical industry from 1 MW to 60 MW boilers. Results show that effectively implementing a gas tax, electricity subsidy, annual grant and carbon tax can generate sufficient demand-pull to reduce the cost of electric boilers from 30 to 85 % depending on the boiler size. A carbon tax starting at £280 per tCO_2e and reducing to £170 per tCO_2e coupled with electricity subsidies is essential for this transition. The policies are designed such that a win-win is achieved between government and industry; specifically, revenue from the carbon tax and gas tax is used to support the grant and electricity subsidy thereby achieving cost neutrality for government. At 100 % uptake of electric boilers in 2033, the total carbon emissions reduce by 89 %, which is above the 2035 UK industry goal of 60 % reduction. The research establishes a robust policy timeline that can drive industrial electrification in the UK's chemical sector. It highlights the need for a multi-faceted approach, incorporating various policy instruments to overcome the barriers of high initial capital costs.

1. Introduction

In 2020, the Chemical Industry accounted for 2.3 Gt of GHG making up 6% of global emissions (Eryazici et al., 2021). This sector is often referred to as an Energy Intensive Industry and labelled “hard-to-abate” (IEA, 2021). Reducing emissions in the chemical industry is crucial because it is closely interconnected with other societal and technical systems (Chung et al., 2023). Therefore, achieving the goals of the Paris Agreement necessitates a collective 46 % reduction in emissions from the chemical industry to limit the temperature increase to 1.5 °C (Talaei et al., 2018). This reduction can be achieved through the adoption of alternative technologies such as electrification of heat, carbon capture and utilization and advance recycling techniques, as well as the uptake of other alternative sources of energy such as biomass, and green hydrogen. However, the transition to these alternative fuels and technologies is hindered by the significant capital investment required (Stančin et al., 2020). To address these concerning statistics and align with global commitments, the UK has established the Net Zero Innovation Portfolio (NZIP), aiming for net-zero emissions by 2050, with interim targets set for 2035. Industrial emissions must be reduced by two-thirds compared to 2018 levels (HM Government, 2021), and electricity generation systems fully decarbonised by 2035, according to the government (BEIS, 2021). To meet these targets, the Climate Change Committee, an external statutory body, expects a 56 % reduction in the current 11.55 $MtCO_2$ emitted by the UK Chemical Industry, which is predominantly privately-owned (EcoAct, 2023).

The UK chemical sector heavily relies on fossil fuels feedstock such as

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Notations

$G_{i,cons}$	Gas Consumption (MWh/yr)
$E_{i,t}$	Electricity Consumption (MWh/yr)
W_i	Energy Output Electric Boiler (MWh/yr)
$y_{i,bt}$	Binary Variable
$M_{U,t}$	Market Share (%)
$\tau_{g,t}$	Gas Tax (%)
$\tau_{c,t}$	Carbon Tax (%)
$s_{e,t}$	Electricity Subsidies (£/MWh)
g_t	Grant (%)
$ACOH^{post}_{e,i,t}$	Annualised Cost of heating electric boiler after policy application. (£/yr)
$ACOH^{post}_{g,i,t}$	Annualised Cost of heating gas boiler after policy application. (£/yr)
$GC_{i,t}$	Cost to government (£)
$IC_{i,t}$	Cost to industry (£)
TCB_t	Total Cost bound (£)
$R_{e,i,t}$	Electricity subsidies for each boiler (£/yr)
$G_{e,i,t}$	Grant allocated to each boiler (£/yr)
$CT_{g,i,t}$	Carbon tax on natural gas consumption
$CT_{e,i,t}$	Carbon tax on electricity consumption
$T_{g,t}$	Natural gas tax
ε_g	CO_2 emission factor natural gas (t CO2e/MWh)
H_{op}	Yearly operating hours
A_g	Natural gas boiler availability (%)
A_e	Electric boiler availability (%)
F_{gb}	Fixed Operating & maintenance cost (£/kW/yr)
α_{ngb}	CAPEX natural gas boiler (£/kW)
η_g	Natural Gas Boiler Efficiency (%)
η_e	Electric Boiler Efficiency (%)
$g(t)$	Natural Gas Price with CCL (£/MWh)
$e(t)$	Electricity Price with CCL (£/MWh)
$\mathrm{f(t)}$	Electric Emission Factor (t CO2e/MWh)
α_{eA}	Electric Boiler CAPEX A coefficient
α_{eB}	Electric Boiler CAPEX B coefficient
r_e	Discount rate electric boiler (%)
$NIC_{i,e,t+1}$	New Investment Cost of electric boiler (£/yr)
L_e	Electric Boiler Lifetime (yr)
$LIC_{e,t}$	Levelised Investment cost electric boiler (£/yr)
$N^{m}_{0,t}$	Installed capacity per cluster (MW)
N^{m}_{t}	Initial cluster capacity (MW)
$VOM_{e,t}$	Variable O&M costs (£/yr)
$FOM_{g,t}$	Fixed O&M costs (£/yr)
$ACOH^{pre}_{e,i,t}$	Annualised cost of heating electric boiler before policy application. (£/yr)
$ACOH^{pre}_{g,i,t}$	Annualised cost of heating gas boiler before policy application. (£/yr)
LP	Learning parameter

Subscript

i:	For boiler in range i
g:	Gas boiler
e:	Electric boiler
c:	Carbon Dioxide
bt:	Binary variables of electric boiler
op:	Operating hours
t	Time

naphtha and ethane for producing olefins, aromatics, and ammonia intermediates. The industry is also the largest consumer of natural gas in the UK for process heating and power generation, with an annual consumption of 26.3 TWh (Durusut Emrah, 2019). Utilizing technologies such as Combined Heat and Power (CHP), boilers, and furnaces for generating steam required for cracking, reforming, and downstream processing of intermediates, which demand temperatures up to 900 °C (Vogelpohl, 1988; Young et al., 2022). On-site burning of fossil fuels for heat to meet these demands accounts for 60 % of the sectors total emissions, whilst electricity contributes 23 % of emissions (Viisainen Verner, 2023). The Government energy consumption statistics indicate that approximately 73 % of the current fossil fuel heating is for low temperature processes below 500 °C (Bala and Shuaibu, 2022). Therefore, this energy demand can be switched to electricity. This presents an opportunity for alternative technologies such as electric boilers, capable of meeting heat demand up to 600 °C (Madeddu et al., 2020), powered by renewables or a decarbonised electricity generation system. Electric boilers offer higher efficiency than gas boilers and are more suitable for low to medium heat applications compared to alternatives like hydrogen or carbon capture and storage (CCS) (Madeddu et al., 2020).

Furthermore, the adoption of electric boilers is critical for the UK since emissions are evenly split between clusters and dispersed sites (HM Government, 2021), and many of these dispersed sites lack access to hydrogen or CCS infrastructure (Geels et al., 2023). Electrification can be implemented in industry without waiting for pipeline infrastructure, enabling early adoption and emission reduction as soon as 2023 (Element Energy, 2020). Barriers slowing the adoption of electric boilers and renewable electricity in the industrial sector are the high initial capital cost of the technology and the cost of alternative fuels relative to fossil fuel-based counterparts resulting in higher operational costs (Rissman et al., 2020). To overcome these barriers, there is a need for an effective timeline of long-term market-based policies inducing a technology transition to cleaner production of steam which is critical for the chemical sector to meet the UK's 2035 industrial goal. Yet there is no systematic way to design and quantify the impact of market-based policies especially in generating sufficient demand-pull from industry for the alternative fuel. This work posits that effective market-based policies reduce cost and generate sufficient demand-pull to trigger further cost reduction until there is 100 % switch to electric boilers, and the journey to 100% uptake (i.e., diffusion pathway) can be exploited to further reduce the total mitigation cost (includes cost to government and industry). Furthermore, effective market-based policies achieve a higher reduction in carbon emissions at a lower mitigation cost.

This work introduces a novel multi-period market penetration optimisation model designed to evaluate the impact of policy support in reducing cost and generating sufficient demand-pull for electric boilers to trigger further cost reduction according to the technology learning using existing inventory of natural gas boilers within the UK's chemical industry. Utilizing a multi-period Mixed-Integer Nonlinear Programming (MINLP) approach, the model considers various policy scenarios to inform decisions about transitioning from natural gas to electric boilers. Economic factors, governmental incentives, and environmental impacts are integrated into the model to measure the total cost implications for both the government and the industry. This multi-period framework allows for a phased adoption of sustainable technologies, providing a roadmap for policy interventions required to accelerate market penetration of electric boilers. By doing so, this research aims to establish a timeline for future policies that can drive industrial electrification of heat. The subsequent literature review will critically examine the application of electric boilers in the UK's chemical sector. It will focus on current methodologies, governmental policy modelling, and the barriers to long-term adoption. The aim is to identify gaps in existing research and offer actionable insights for the effective transition to sustainable technologies, guided by well-modelled policies.

2. Literature review

The technological readiness of electric steam boilers has been well-established, achieving a Technology Readiness Level (TRL) of 9 (Madeddu et al., 2020). In contrast, heat pumps capable of operating at temperatures above 160 °C have reached a TRL of 6 (Madeddu et al., 2020). Electric heaters, which are commercially available in capacities up to 70 MWh, offer versatile applications in producing both steam and liquid heating media. These heaters can operate as electric resistance or electrode boilers for steam generation and as electric resistance heaters for liquid heating (Maruf et al., 2022). Direct electrification of industrial process heat has been shown to be applicable across various operational levels within the chemical sector, including central sites, sub-central operations, and unit operations (Kochenburger et al., 2023; Tłałka, 2020). An assessment of the Dutch industry showed electric boiler have up to 99.9 % efficiency compared to gas boiler with up 90 % efficiency (denOuden et al., 2017). Despite the technological readiness, the adoption rate of electric boilers remains low. Energy-Intensive Industries (EIIs) face several barriers to innovation, such as market structures, high capital requirements, and long investment cycles prioritize between competing capital projects (Kiemel et al., 2023; Wesseling et al., 2017). An Adoption Heuristics study further categorized electric boilers as secondary to production or product quality improvements, resulting in a mere 10 % adoption rate for electrification of heat technologies in the USA (Mai et al., 2018).

Techno-economic assessments (TEAs) have been applied to evaluate the feasibility and impact of electric boilers in the chemical industry. For example, a study on an existing Oxo synthesis plant simulated a significant emissions reduction of 333 kt/a but encountered challenges when energy costs increased by 100 % (Wiertzema et al., 2020). Other TEAs have focused on integrating electric boilers into the heat exchange network to meet onsite steam demand (Kim et al., 2022), or electrifying industrial boiler systems in different sectors in the USA (Zuberi et al., 2022). These studies have all collectively highlighted the environmental benefits of electric boilers, particularly when the electricity used is generated from cleaner sources than natural gas (Han et al., 2017), they often overlook the impact of cost reductions in electric boilers or fuel due to policy induced demand-pull and associated experiential learnings. This gap in the literature highlights the need for Market Penetration Models that can leverage these insights to facilitate successful adoption. From an energy system modelling perspective, some studies have assessed the impact of heat electrification. These studies often model the role of electric boilers coupled with high-temperature storage or hybrid CHP systems for negative flexibility (Bauer et al., 2022). The findings generally favour electrification over hydrogen-based processes due to lower system costs and higher efficiency (Mersch et al., 2023; Sorknæs et al., 2022). (Aunedi et al., 2022) applied a multi-model approach to develop decarbonisation pathways for heat through a combination of electrification and hydrogen. While these models highlight the potential for emissions reduction and validate the technology readiness of electric boilers, they often neglect the impact of reducing fuel and technology costs from policy induced demand-pull. Furthermore, these models have not been used to explore adoption pathways, especially how they can further reduce mitigation cost.

In the context of the UK industry, transitioning away from fossil fuel boilers has largely been on biomass and hydrogen options (Griffiths et al., 2021). This is often attributed to concerns about energy security and affordability, as well as the need to meet occasional high-temperature heat demands. A recurring theme in the literature is that the extent of heat electrification is strongly influenced by the relative prices of natural gas and electricity (Mersch et al., 2023). Several macro uncertainties, such as fluctuating energy prices due to supply-demand imbalances, seasonal variations, and geopolitical factors like the war in Ukraine, have led to unprecedented spikes in electricity prices (19.3–23.9 p/kWh) and natural gas prices (4.6–4.8 p/kWh) in (Statista, 2022a, 2022b). These price surges, which were on average 4–5 times higher than usual, have significantly escalated production costs in the chemical industry. In response, the UK government introduced a short-term Energy Bill Discount Scheme (Department for Business and Trade, 2023). According to data from the International Energy Agency (IEA), the UK had the highest average industrial electricity prices among 31 countries in 2021. Conversely, it ranked 18th lowest in gas prices on a Purchasing Power Standard (PPS) per kWh basis (BEIS, 2023b). The higher electricity prices, relative to natural gas, act as a deterrent to switching to lower-carbon electric heating options. Addressing this cost disparity must be a priority for policy reform (Climate Change Committee, 2020).

Sweden serves as a relevant case study in this context; the country has managed to reduce the price gap between electricity and gas to less than half the European average, enabling innovation in steel and cement production (Philibert, 2017). Fig. 1, enthesis that this price disparity was up to six times higher in 2019, largely because electricity prices bear the brunt of climate policy costs. Furthermore, the average industrial consumer of gas pays only 13% of gas prices in tax, compared to 34–38% in taxes on electricity. There is a pressing need to further investigate the role of taxes and electricity subsidies in incentivizing fuel switching. Therefore, the adoption of electric boilers is highly dependent on effective government policy interventions.

While policies that could make electric boilers commercially attractive theoretically exist, there is still a need to quantify their actual impact on adoption rates, patterns, and mitigation costs. Although the UK Emissions Trading System (ETS) incentivizes industrial electrification, evidence suggests this is not happening (Climate Change Committee, 2020), and current policies for heat decarbonisation is limited to R&D grants for Technology readiness level 4 to 7 (Geels et al., 2023). This underscores the urgent need to explore new policy scenarios that focus specifically on electric boilers, to align with the UK's 2035 industrial decarbonisation goals. There is a strong need for grants to be applied to the whole market to accelerate adoption. Various factors can enable electrification in the industry, including cost-competitive low-carbon power generation methods like wind, solar, biomass, and small-scale nuclear. The sector has the potential to develop new business models that increase on-site renewable generation, reduce transmission losses, and enhance energy efficiency. Consequently, there is a pressing need to design efficient policies that provide both capital expenditure (CAPEX) and operational expenditure (OPEX) support, incentivizing the industry to adopt alternative technologies such as electric boilers (Viisainen Verner, 2023). However, the electricity prices are projected to stay 2.7 times higher than gas prices in the long-term (BEIS, 2023a), highlighting the challenges that lie ahead.

The process of designing industrial policies is iterative and dynamic, requiring inputs from numerous parties impacted by the policy (Haeri and Arabmazar, 2019). Optimisation models play a crucial role in this context by providing deterministic frameworks that capture relationships and trade-offs. These models aim to facilitate informed decision-making. Studies have employed Mixed-Integer Linear Programming (MILP) models to assess the effectiveness of carbon taxes in inducing a transition to cleaner technologies. For example, (Wolf et al., 2023) demonstrated that carbon taxes alone are insufficient for this purpose. Existing approaches often lack the complexity needed to capture real-world systems, which frequently exhibit nonlinear behaviour and require discrete decisions. This highlights the need for more sophisticated modelling approaches, such as Mixed-Integer Nonlinear Programming (MINLP) market penetration models, which can account for multiple temporal periods and a combination of policies simultaneously.

In essence, policy shapes the transition to sustainable industrial practices through a mix of incentives, regulations, and support (Hafner et al., 2022). Existing literature primarily focuses on the electrification outlook as a transition route for industries, with bottom-up energy models like FORECAST (Fleiter et al., 2018) being developed to consider fuel-switching policies. These models have been applied to German

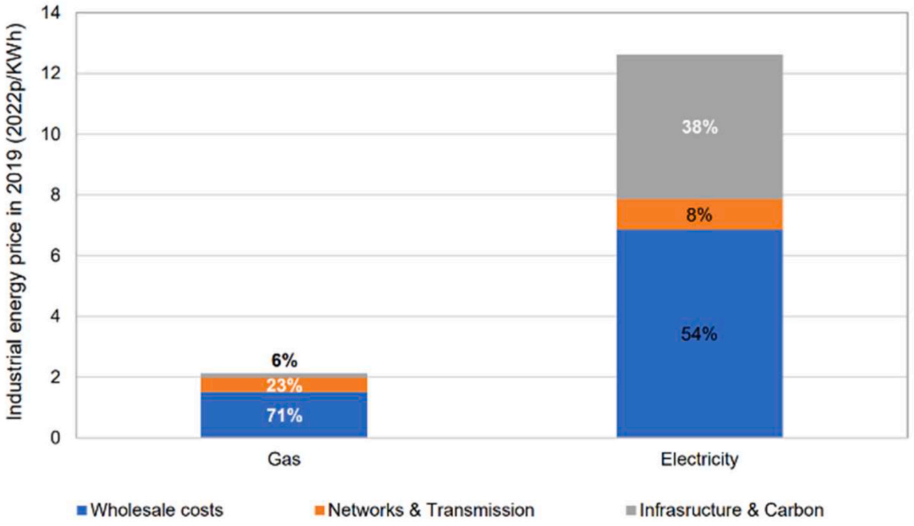

Fig. 1. Industrial natural gas and electricity prices in 2019 (Statista, 2022a, 2022b).

industries to evaluate the impact of carbon pricing and subsidies under various scenarios, ranging from no support to stringent regulatory bans on fossil fuel-based steam generation (Rehfeldt et al., 2020). While these models show that hard regulation coupled with government support results in the lowest system costs in relation to greenhouse gas emissions, they lack a comprehensive approach that shows how lowering the system cost can generate sufficient demand-pull to trigger further cost reduction until the technology becomes cost competitive. Furthermore, other FORECAST studies have assumed a flat policy support rate for electric steam boilers (Fleiter et al., 2019). These studies do not account for how external influences can increase demand and lead to cost reduction from technology learning rates using mechanisms like governmental interventions, economies of scale, and market dynamics.

While the impact of learning rates on reducing technology costs is well-studied, particularly in the context of renewable energy capacity building (Lambert and Oluleye, 2019), the learning parameter for electric boilers remains largely unexplored. The closest study available is a meta-analysis that used model-driven engineering (MDE) software with endogenous learning curves but concluded a learning parameter of 5% for electric boilers due similarity to condensation boiler (Rubin et al., 2015). This approximate learning parameter means the cost of electric boilers reduces for every doubling of capacity associated with increasing demand-pull. The lack of data on electric boiler production and learning parameter necessitates further research to quantify its impact on both adoption and overall system costs. Integrating technology learning is crucial for policymakers to identify the most cost-effective interventions, such as subsidies or taxes, to stimulate demand.

The diffusion of electrification of process heat in the industry has been less frequently studied (Rehfeldt et al., 2018). The non-linear aspects of technology diffusion through time are captured with an s-curve model, which are characteristic of real-world scenarios. Adoption is typically slow at the beginning and end but rapid during the middle phase. Current literature delves into the intricacies of s-curve diffusion models, linking them to technological improvement rates and the timing of key events in the adoption process (Benson and Magee, 2018; Jeleskovic et al., 2023). In contrast, Linear Diffusion models offer a simpler, more predictable perspective by assuming a constant rate of adoption over time. Technologies with a recurrent nature of innovations often follow a linear diffusion pathway. While easier to analyse, they may not accurately capture the complexities of real-world technology adoption. Given this gap, this study investigates the cost-effectiveness from using both the s-curve and linear diffusion models as an excellent starting point for designing policies that support the uptake of electric boilers and mitigate cost.

Existing literature on policy and innovation primarily focuses on the qualitative aspects of electrification in the chemical sector, emphasizing the need for secure electricity supply, grid access, and technological innovation. However, these studies often overlook quantifying the impact of various policies on the cost-effectiveness of electric boilers and the demand they generate, neither do they consider the interplay of different policies, feedback on electricity prices, and societal opportunity costs. To address these gaps, this study aims to develop a novel multi-period Mixed-Integer Nonlinear Market Penetration Model for industrial heat electrification. Beyond building the model, other objectives are as follows: conduct a case study to explore adoption patterns aiming for 100% market uptake, considering s-curve and Linear adoption models, design an optimal policy timeline leveraging various instruments like gas taxes, carbon taxes, grants, and electricity subsidies to facilitate fuel switching in the chemical industry and evaluate the effectiveness of these policies in reducing the cost differential between government and industry expenditures. This model will also consider the carbon intensity of the grid and the impact of carbon emissions, offering a comprehensive framework for decarbonisation in energy-intensive industries. By doing so, the study provides a holistic approach that can guide decision-making. Moreover, the model can be adapted to explore other decarbonisation pathways and establish a policy framework for different technologies, thereby ensuring the successful uptake of fuel-switching initiatives.

3. Methodology

The market considered in this work is the existing gas boiler population of the UK chemical industry totalling to 490 natural gas boilers consuming 9.6 TWh per year (Tlałka, 2020). It is assumed that each natural gas boiler can be replaced with an equivalent electric boiler. Table 1 contains available electric boiler sizes. Replacing natural gas with electricity is more expensive hence policy intervention is crucial to incentivise fuel switching. The temporal deterministic model is based on yearly OPEX and CAPEX of natural gas and electric boilers and coupled with policies. Time dependent scalar values such as forecasted

Table 1
Number of equivalent electric boilers per cluster.

Clusters (Boiler size)	1 MW	5 MW	9 MW	15 MW	30 MW	60 MW
Number of electric boilers	117	270	44	21	12	26

electricity, natural prices and emission are from government statistics (Bala and Shuaibu, 2022; BEIS, 2023a). The learning parameters showing reduction in investment cost of electric boilers over time is dependent on capacity and fixed operating cost obtained from literature (Zuberi et al., 2022). The objective function (Equation (1)) maximises the total market share (uptake) of electric boilers within a period following a s-curve or linear diffusion, $M_{U,t}$. The Market occupancy of each boiler is calculated by Equation (2). A binary decision variable determines when it is economic to switch and contributes to the new market share (Equation (4)). Vectors x and $y_{i,bt}$ represent the continuous and binary variables respectively.

$$\max_{x,y_{i,bt}} \sum_{i=1}^{I} \left[y_{i,bt} \frac{W_{i,t}}{\sum_{i=1}^{I} W_{i,t}} \right] - M_{U,t}, \tag{1}$$

$$W_{i,t} = G_{cons,i} \eta_g \tag{2}$$

The continuous decision variables are government policies and bounded shown by equation (3). These bounds are obtained from Treasury's green book and literature (BEIS, 2023a; Fleiter et al., 2019).

$$x = \begin{cases} \tau_{g,t} \in [0, 0.2] \\ s_{e,t} \in [0, 100] \\ \tau_{c,t} \in [0, 378] \\ g_t \in [0, 0.5] \end{cases}, \forall_i \in \{1, 2, \ldots, 490\}, \ \forall_t \in \{1, 2, \ldots, 10\}, \tag{3}$$

$$\mathrm{y}_{i,bt} \in \{0, 1\}, \ \mathrm{y}_{i,bt} \geq \ \mathrm{y}_{i,bt-1} \tag{4}$$

Constraints are such that for a switch to happen a policy should stimulate an endogenous cost parity i.e., the annualised cost of heating via electric boiler must be less than or equal to that of natural gas (Equations (5) and (6)). This represents what industrial stakeholders are willing to pay to switch to electrification.

$$\text{s.t.} \ \ ACOH^{post}_{e,i,t} - ACOH^{post}_{g,i,t} \leq 0 \tag{5}$$

$$-\left[ACOH^{post}_{e,i,t} - ACOH^{post}_{g,i,t}\right] - 150,000 \leq 0 \tag{6}$$

The impact of these policies leads to mitigation cost on industry $IC_{i,t}$ and government $GC_{i,t}$. Thus, the total cost TCB_t is constrained to an amount agreed upon by stakeholders shown by equations (7) and (8). The below equations enables cost neutrality in designing policy support.

$$\sum_{i=1}^{I} [GC_{i,t}] - TCB_t \leq 0 \tag{7}$$

$$\sum_{i=1}^{I} [IC_{i,t}] - TCB_t \leq 0 \tag{8}$$

Equations (9) and (10) integrate policies into the economic analysis. The cost to government and industry is dictated by the feed in tariff on electricity, carbon tax generated from electricity and gas consumption, gas tax generated and electric boiler grant.

$$\begin{aligned} IC_{i,t} = y_{i,bt}\big(y_{i,bt} CT_{e,i,t} + y_{i,bt}\big(ACOH^{pre}_{e,i,t} - R_{e,i,t} - G_{i,t} \\ - ACOH^{pre}_{g,i,t}\big) + \big(1 - y_{i,bt}\big)\big(CT_{g,i,t} + T_{g,i,t}\big)\big), \forall i \end{aligned} \tag{9}$$

$$GC_{i,t} = y_{i,bt}\big(y_{i,bt}\big(R_{e,i,t} - CT_{e,i,t}\big) - \big(1 - y_{i,bt}\big)\big(CT_{g,i,t} - T_{g,i,t}\big)\big) + y_{i,bt} G_{i,t}, \forall i \tag{10}$$

Policies such as carbon tax applies to both natural gas and electricity consumption. Which is dependent on the efficiencies of boilers and CO_2 emissions. $G_{i,cons}$ is the gas consumption per boiler. Equation (11) is for natural gas boilers carbon emissions. Whilst for electric boiler carbon emissions follows a scalar time function dependent on electricity grid emission (Equation (12)).

$$CT_{g,i,t} = \tau_{c,t} G_{i,cons} \varepsilon_g, \forall i \tag{11}$$

$$CT_{e,i,t} = \tau_{c,t} W_{i,t} \eta_e \mathrm{f}(t), \forall i \tag{12}$$

The grants, gas tax and subsidies are determined using (Equations (13)–(15)).

$$G_{e,i,t} = g_t LIC_{e,i,t}, \forall i \tag{13}$$

$$T_{g,i,t} = \tau_{g,t} G_{i,cons} \ g(t), \forall i \tag{14}$$

$$R_{e,i,t} = s_{e,t} W_{i,t} \eta_e, \forall i \tag{15}$$

The impact of policy interventions on the annualised cost of heating via electric and gas boiler is shown in equations (16) and (17). Electricity subsidies and grants reduces the cost of electric boiler. Whilst carbon tax on natural gas emissions and consumption tax penalises natural gas boiler usage.

$$ACOH^{post}_{e,i,t} = ACOH^{pre}_{e,i,t} - R_{e,i,t} + CT_{e,i,t} - G_{e,i,t}, \forall i \tag{16}$$

$$ACOH^{post}_{g,i,t} = ACOH^{pre}_{g,i,t} + CT_{g,i,t} + T_{g,i,t}, \forall i \tag{17}$$

The annualised heat cost for gas boilers without policy interventions is given by Equation (18). Which culminates the fixed and variable operating cost.

$$ACOH^{pre}_{g,i,t} = \alpha_{gb} \frac{1000 G_{cons,i}}{H_{op} A_g} F_{gb} + G_{cons,i} \ g(t), \forall i \tag{18}$$

The same is required for electric boiler. The variable cost is $VOM_{e,i,t}$ based on the energy required to meet gas consumption for each electric boiler E_i and the average price of electricity at each period, Equations (19) and (20).

$$E_i = \frac{G_{i,cons} \ \eta_g}{\eta_e}, \forall i \tag{19}$$

$$VOM_{e,i,t} = E_i e(t), \forall i \tag{20}$$

Fixed operating and maintenance cost is a percentage F_{eb} of the levelized investment cost for each electric boiler $LIC_{e,i,t}$, given by Equation (21),

$$FOM_{g,i,t} = LIC_{e,i,t} \ F_{eb}, \forall i \tag{21}$$

The levelized investment cost is dependent on the electric boiler required capacity to replace a natural gas boiler. Consisting of electricity consumption, availability and operating hours, Equation (22). The capacity is rounded to nearest cultural size as shown in Table 2 and Equation (23).

$$C_{e1,i,t} = \frac{E_i}{H_{op} A_e}, \forall i \tag{22}$$

Table 2

Fixed Parameters in model.

Year	Electricity Price with CCL (£/MWh)	Natural Gas Price with CCL (£/MWh) (BEIS, 2023a)	Electric Emission Factor (t CO2e/MWh)	S-Curve	Linear adoption
	BEIS (2023a)		BEIS (2023a)		
2023	128	26.7	0.152	0	0
2024	130	29	0.146	0.01	0.1
2025	121	31	0.127	0.04	0.1
2026	124	32	0.095	0.09	0.1
2027	131	33	0.07	0.16	0.1
2028	131	34	0.061	0.2	0.1
2029	128	35	0.052	0.2	0.1
2030	128	36	0.048	0.16	0.1
2031	128	36	0.04	0.09	0.1
2032	130	36	0.032	0.04	0.1
2033	130	36	0.025	0.01	0.1

$$C_{e,i,t} = \begin{cases} 1 & if\ C_{e1,i,t} \leq 1 \\ 5 & if\ 1 < C_{e1,i,t} \leq 5 \\ 9 & if\ 5 < C_{e1,i,t} \leq 9 \\ 15 & if\ 9 < C_{e1,i,t} \leq 15 \\ 30 & if\ 15 < C_{e1,i,t} \leq 30 \\ 60 & otherwise \end{cases} \tag{23}$$

Investment cost of each electric boiler is calculated based on allocated cluster size and the marginal investment cost from parameters α_{eA} and α_{eB}, Equation (24).

$$ICB_{e,i,t} = C_{e,i,t} 1000 \alpha_{eA} C_{e,i,t}^{\alpha_{eB}}, \forall i \tag{24}$$

The impact of created demand-pull on technology cost reduction resulting in a new investment cost for the next period is provided in Equation 25 – where LP is the learning parameter, installed capacity per cluster N_t^m and size of cluster N_0^m.

$$NIC_{e,i,t+1} = ICB_{e,i,t} \left(\frac{N_t^m}{N_0^m} \right)^{-LP}, \forall i \tag{25}$$

From the new investment cost a yearly levelized investment cost is established for each electric boiler. This is based on the life span of the boiler and a discount rate, equation (26). Which culminates to the expected heat cost electric boilers before policy support, equation (27).

$$LIC_{e,i,t} = \frac{NIC_{e,i,t+1} r_e (1+r_e)^{L_e}}{(1+r_e)^{L_e} - 1}, \forall i \tag{26}$$

$$ACOH_{e,i,t}^{pre} = FOM_{e,t} + VOM_{e,t} + LIC_{e,i,t}, \forall i \tag{27}$$

The model have been implemented in Python 3.11, Pyomo 6.5.0 and a third party extension Mindtpy MINLP problem solved with CPLEX 22.1.1.0 and IPOPT 3.14.9 (Goyal and Ierapetritou, 2007). Previous works have focused on global solvers branch and bound method whilst this method utilised Feasibility Pump as the initialization strategy and Outer-Approximation (OA) algorithm (Bernal et al., 2020). The problem totalled 984 constraints and 496 variables. Link to the python model can be found in the supplementary information.

The fixed parameters for the model are provided in Tables 2 and 3 and time dependent scalar variables in Table 4.

4. Main findings

Using the model in Section 3, results for the policy designed and mitigation costs for the linear adoption and s-curve are shown in Figs. 2 and 3. The figures also show the financial implications to both the government and industry, illustrating the costs associated with implementing policies aimed at achieving 100 % adoption of electric boilers over a 10-year horizon. About 12.5 million £ is required to stimulate the market based on the S-curve adoption, and 87 million £ for the linear curve. Ideally the amount required to stimulate market-demand should be determined based on government budget constraints. Accelerating uptake of electric boilers requires all policies – carbon tax, gas tax, annual grant, and electricity subsidy. The revenue from taxes is used to fund the annual grant and electricity subsidy resulting in a cost neutral uptake. It is more cost-effective to implement all four policies than any single one.

Table 3
Technology assumptions.

Parameter Name	Value
Natural Gas Boiler Efficiency	0.9
Electric Boiler Efficiency	0.99
Natural Gas Boiler Lifespan (Year)	30
Electric Boiler Lifespan (Year)	20
Operating Hours (h)	3260
Natural Gas Boiler Availability	0.9
Electric Boiler Availability	0.99
Natural Gas Emission Factor (t CO2e/MWh)	0.184
Natural Gas Boiler Discount Rate	0.035
Electric Boiler Discount Rate	0.05
Natural Gas Boiler CAPEX (£/kW)	166
Electric Boiler CAPEX A	187.5935539
Electric Boiler CAPEX B	−0.370877617
Natural Gas Boiler Fixed O&M Cost (£/kW/Yr)	0.02
Electric Boiler Fixed O&M Cost (£/kW/Yr)	0.01
Learning Rate	0.05

Table 4
Time dependent scalar values.

Year	Electricity Price with CCL (£/MWh) BEIS (2023a)	Natural Gas Price with CCL (£/MWh) (BEIS, 2023a)	Electric Emission Factor (t CO2e/MWh) BEIS (2023a)	S-Curve	Linear adoption
2023	128	26.7	0.152	0	0
2024	130	29	0.146	0.01	0.1
2025	121	31	0.127	0.04	0.1
2026	124	32	0.095	0.09	0.1
2027	131	33	0.07	0.16	0.1
2028	131	34	0.061	0.2	0.1
2029	128	35	0.052	0.2	0.1
2030	128	36	0.048	0.16	0.1
2031	128	36	0.04	0.09	0.1
2032	130	36	0.032	0.04	0.1
2033	130	36	0.025	0.01	0.1

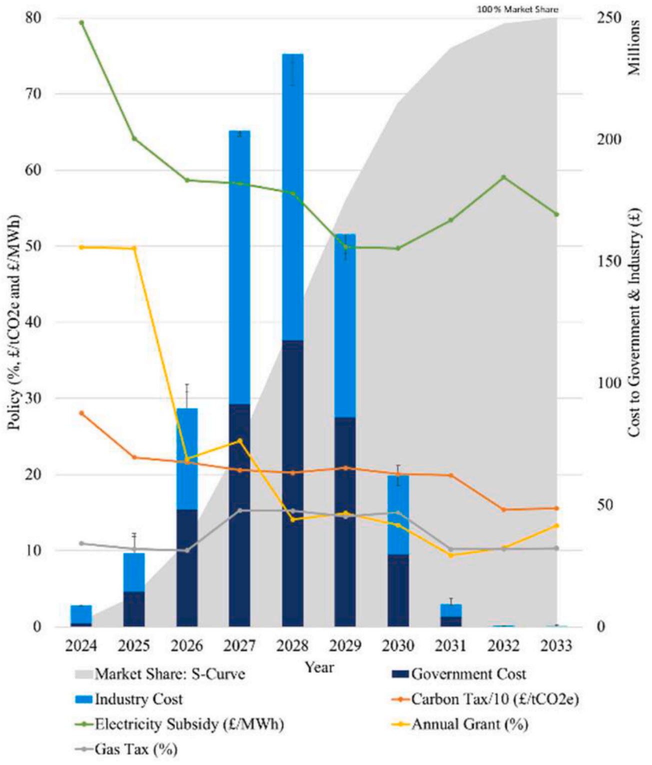

Fig. 2. Market penetration outcome based on the S-Curve adoption.

With the optimal design of the four policies (gas tax, electricity subsidy, annual grant, and carbon tax) sufficient demand-pull is generated to drive down the cost of electric boilers and increase uptake to 100 % in 2033. Individual policy offerings are shown in Figs. 4–7 for the two adoption pathways. The resulting impact of these policies on the economics of 1 MW natural gas and electric boilers are captured in Fig. 8. Overall, heating via electric boilers becomes more cost-effective than natural gas boilers after the implementation of these policies. The effect on CO_2 emissions is shown in Fig. 9. A higher emissions reduction

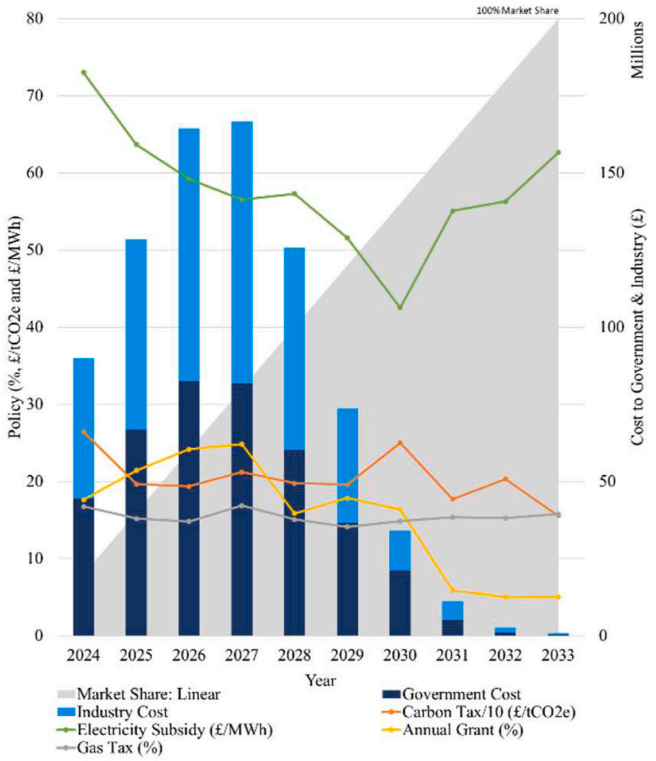

Fig. 3. Market penetration outcome based on Linear adoption.

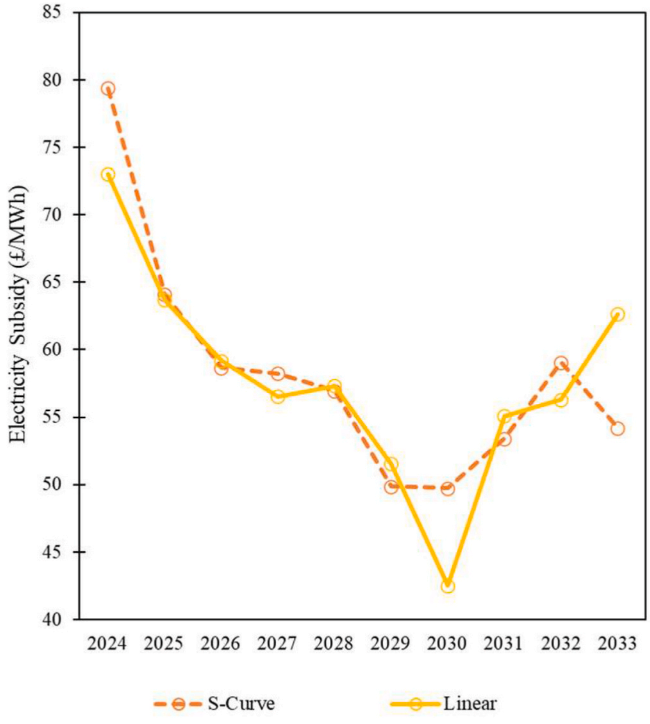

Fig. 4. Designed electricity subsidies for S-curve and linear adoption.

ambition can be reached compared to both the UK industry goal and CCC recommendation. Reduction in the capital cost of boilers due to demand-pull generated from policies for the adoption pathways are shown in Figs. 10 and 12. The implemented policies have led to a notable reduction in the average annualised cost of heating via electricity as compared to gas, a trend that is evident across all boiler clusters. The highest cost reduction is observed for the 5 MW boiler in both pathways (Figs. 10 and 12). This cost-effectiveness is largely attributable to demand-pull from supportive policies.

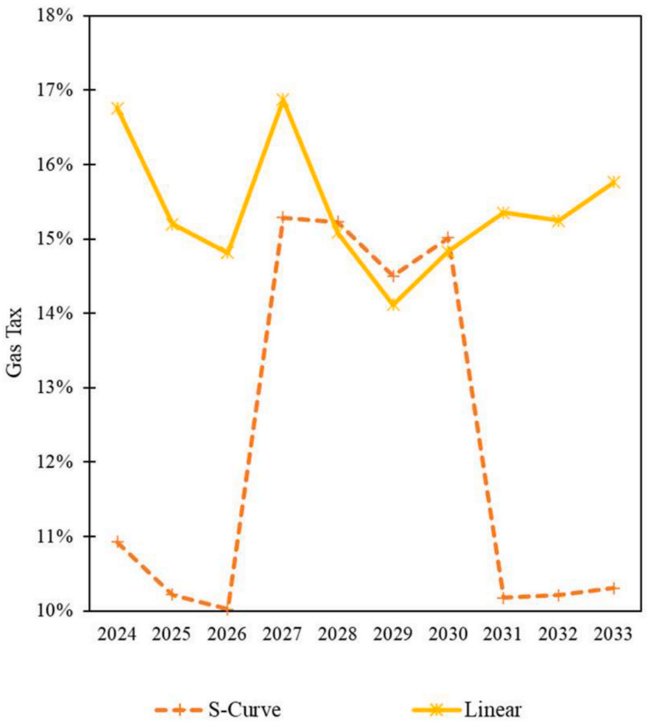

Fig. 5. Designed annual grant for S-curve and linear adoption.

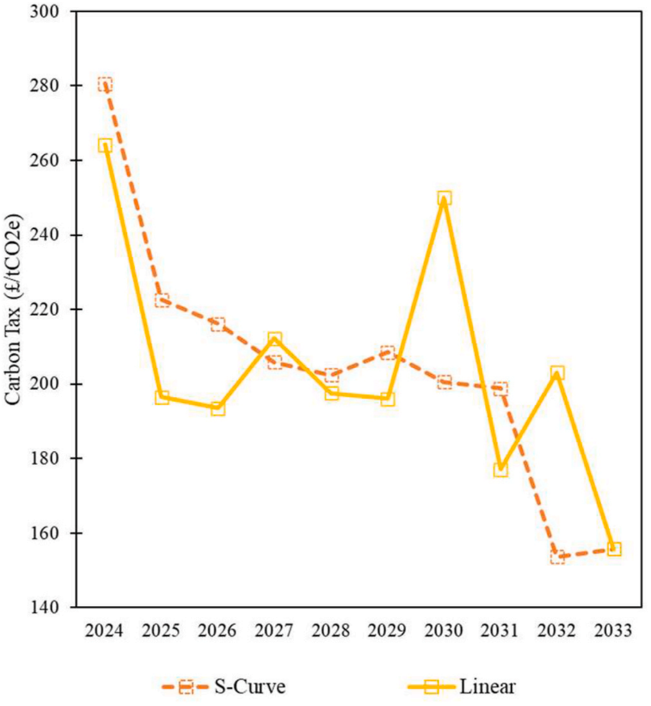

Fig. 6. Designed carbon tax for S-curve and linear adoption.

Figs. 11 and 13 are the granular results for each boiler showing the switch required to achieve the targeted market share for both the linear and s-curve adoption scenarios. Demand-pull from boilers and technology experiential learning determines the new investment costs for subsequent years of uptake, as depicted by Figs. 10 and 12. The cost

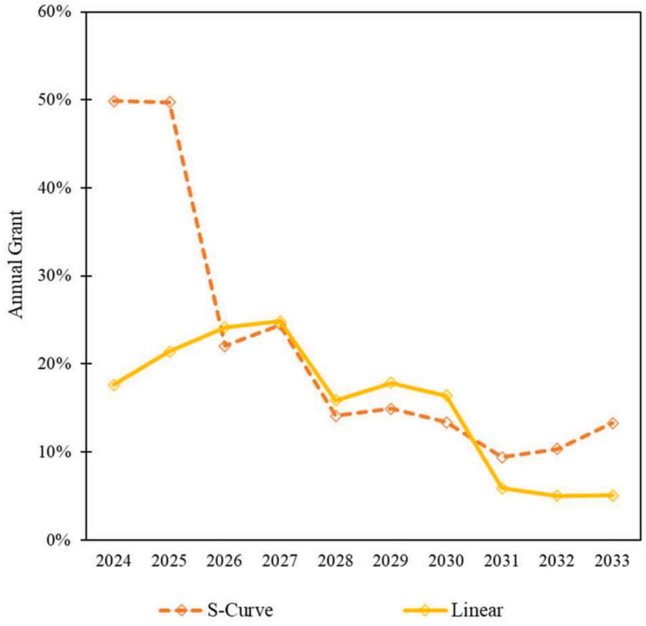

Fig. 7. Designed gas tax for S-curve and linear adoption.

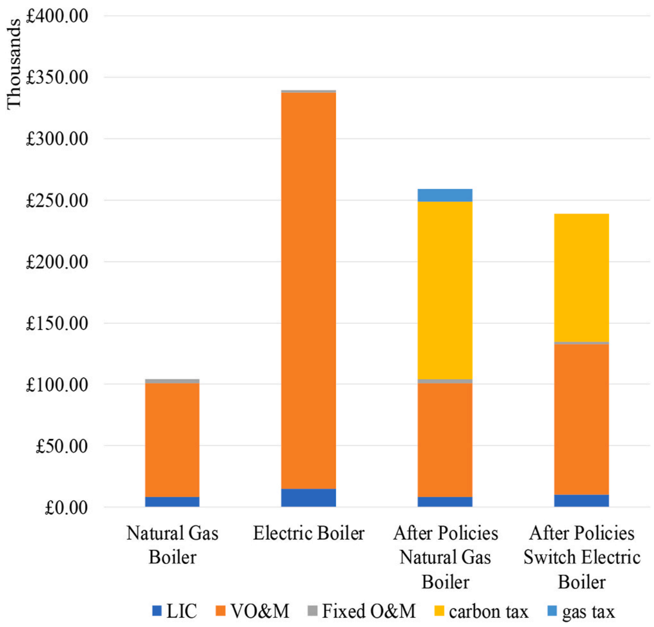

Fig. 8. Yearly economic cost of 1 MW Natural gas boilers before and after policies.

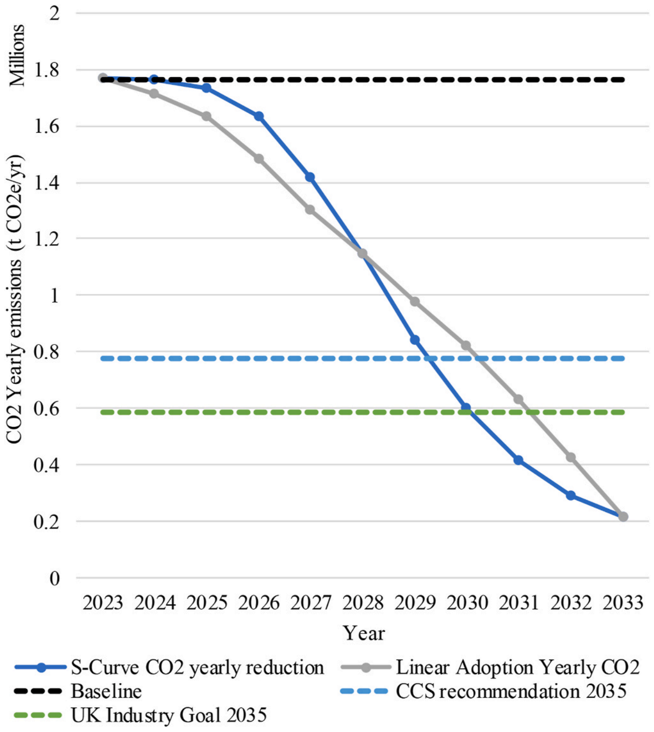

Fig. 9. CO_2 emission reduction from both pathways compared to a baseline of 100% natural gas boilers, and two 2035 goals.

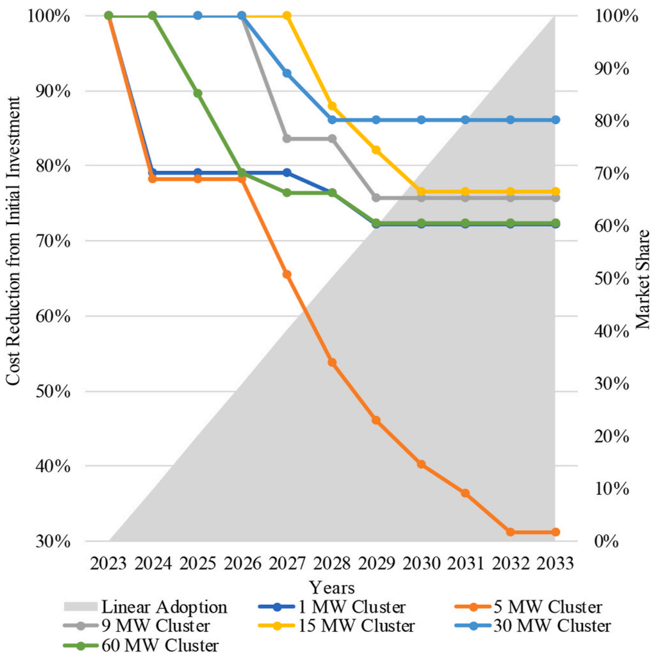

Fig. 10. Cost reduction as a percentage from initial investment for Linear adoption.

analysis reveals that the yearly financial burden on the government is from the electricity subsidy and grants. These are offset by revenues generated from carbon taxes on electricity and gas consumption, as well as natural gas taxes. These dynamic forces the industry to choose between continuing with elevated natural gas boiler operation or switching to more cost-effective electric boilers. Overall, the distribution of costs between industry and government remains balanced, regardless of the adoption pattern resulting in cost neutral policy making (Figs. 2 and 3). The net cost of adopting electric boilers is marginally lower in the linear model by 0.5 % compared to the s-curve model. This difference is attributed to the faster uptake of electric boilers in linear adoption, which doesn't rely on the slower market penetration rates seen among innovators and early adopters. This observation also highlights the role of learning parameter in reducing costs and its role when driving industrial policy improvement over time (Coyle and Muhtar, 2021). Whilst linear diffusion models oversimplify the adoption process, ignoring the influence of social networks and individual characteristics (leung, 2022). S-curve model may not adequately capture the effects of external factors such as market competition or regulatory changes (Radpour et al., 2021). Which play a pivotal role as banning the sale of natural gas boilers, has shown to accelerate the transition to electric

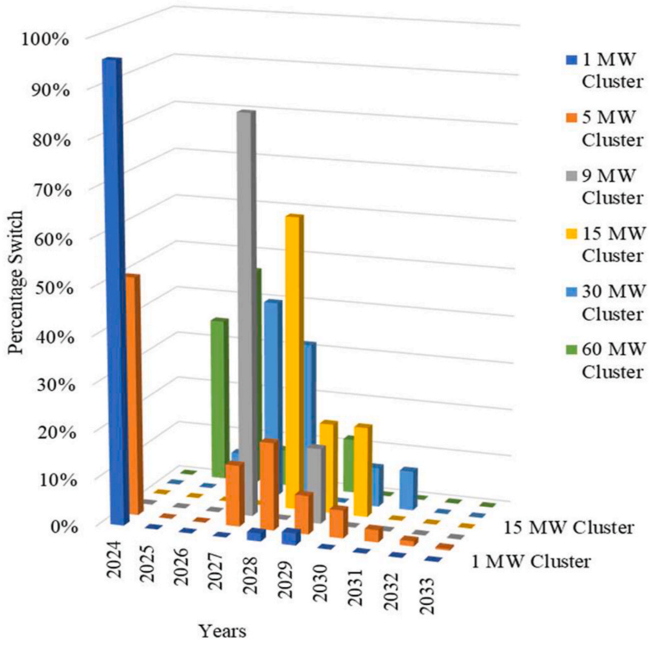

Fig. 11. Percentage of boiler within a cluster switching from natural gas to electric for Linear adoption.

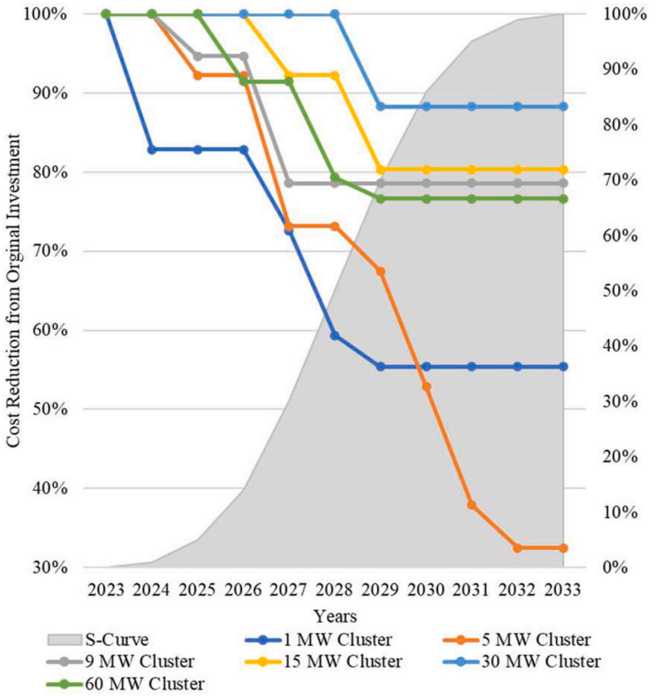

Fig. 12. Cost reduction as a percentage from initial investment for S-curve adoption.

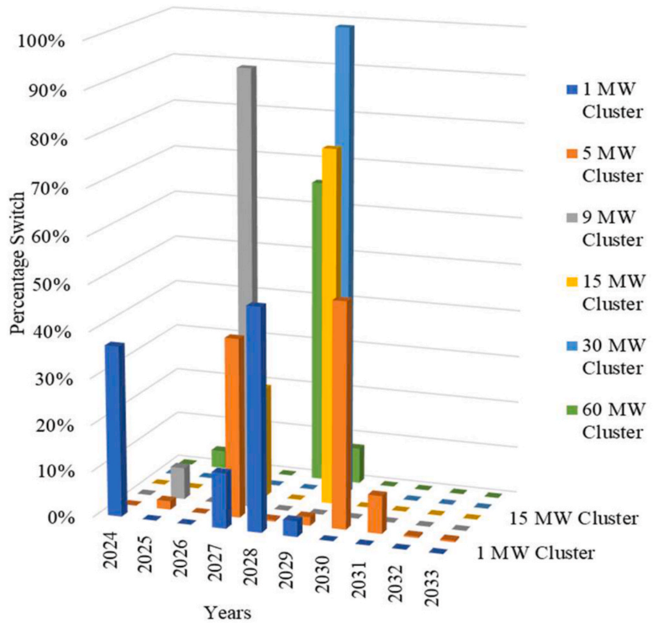

Fig. 13. Percentage of boiler within a cluster switching from natural gas to electric for S-Curve adoption.

boilers (Rehfeldt et al., 2020). Despite this limitation, adoption patterns reduce the mitigation cost.

A carbon tax is a critical policy lever for encouraging the transition to electric boilers. The study indicated than an initial carbon tax starting at £280 per tCO2 and gradually reducing to £170 per tCO2 is necessary for transition to occur. These findings are consistent with international trends; for example, Germany anticipates a carbon tax of up to £300 per tCO2 (Rehfeldt et al., 2020), and even higher rates are expected in Switzerland for electrification of heat in industry. Interestingly, the carbon tax decreases by 60 % over the study period. Several factors could contribute to this decline. This could be attributed to the demand-pull induced learning parameter, which could make the technology cheaper and thus require less carbon tax incentive over time. Another explanation could be the increasing adoption of electric boilers, coupled with a decrease in grid emissions, which collectively reduces the need for a high carbon tax to maintain a competitive annualised cost of heating compared to natural gas. This is consistent across both the linear and s-curve adoption patterns. Electricity subsidy, particularly via feed in tariffs, serve as a potent tool for incentivizing industry adoption. Early stages of adoption, a notably high subsidy rate of £75/MWh is observed, reflecting the need for robust policy support to encourage innovators. However, this rate declines to between £50-£60/MWh after the initial three years (Fig. 4). Unlike the carbon tax, the electricity subsidy remains relatively stable, possibly due to sustained electricity pricing. An outlier observation in 2030 disrupted this trend, electricity subsidy further reduces to £43/MWh, while the carbon tax increased to £255/tCO_2 breaking the prevailing trend and highlights the complex interplay between these two policies instruments. Other studies, which have restricted subsidies to only €20/MWh, may have overlooked this nuanced interaction (Rehfeldt et al., 2020).

Gas tax levels vary between linear and s-curve adoption models. The s-curve model, experiences fluctuations, with a noticeable spike between 2027 and 2030, attributed to rapid adoption phases representing 73% of the target market, necessitating greater incentives to facilitate the switch (Fig. 7). In contrast, the linear model maintains a stable gas tax, reflecting its consistent market share gain. While one might expect a similar trend for grants, the reality is more nuanced due to the impact of the learning parameter (Fig. 5). Both linear and s-curve models allocate fewer grants to late adopters and laggards over time and when technology cost are high in early years of adoption greater incentives are required. This suggests that as the market matures and net investment cost decreases, the need for grant support diminishes. Grants are particularly high during the initial two years of s-curve adoption, especially for boilers within the 1 MW clusters. This underscores the need for robust capital expenditure support for early innovators, who face higher risks and uncertainties in the nascent stages of technology adoption.

The technology cost reduction based on policy induced demand-pull and the learning parameter, are shown in Figs. 10 and 12. Observed clusters such as the 5 MW experience the greatest cost reduction compared to 30 MW clusters. This is due to the larger number of electric boilers in the cluster. Regardless of the adoption pathway be it linear or s-curve findings indicate that a switch from natural gas to electric boilers will result in lower yearly emissions (Fig. 9). This outcome is contingent upon the electricity grids ongoing decarbonisation efforts. As the grid becomes cleaner, the environmental benefits of electric boilers become increasingly significant. It's important to note that the environmental advantages of transitioning to electric boilers are closely tied to the broader energy system's rate of decarbonisation. For instance, in 2022, direct electricity use had a higher emission factor than natural gas due to lower-than-expected renewable energy generation (National Grid Electricity System Operator, 2020). Thus, the environmental benefits are conditional on systemic changes that reduce the carbon intensity of electricity. Further studies can build on this model by incorporating the cost of onsite low carbon electricity generation. This study does not account for the costs and transformation efforts required to make the electricity system a low-emission energy supplier or the infrastructure required to install high voltage connections for 60 MW electric boiler which vary based on geophysical location of each boiler ranging from £100,000/MW to £1,700,000/MW which can significantly add additional cost.

While incentives may be in place for immediate switching to electric boilers, the role of investment cycles can significantly influence the effectiveness of policy incentives and competing against other low carbon technology such as hydrogen or biomass. The need to conduct surveys out of the 490 boiler which are likely to be decommissioned can increase the accuracy of policy allocation and the adoption pattern will be model indicative of the real world. Additionally, there is a need to enhance the deterministic model to develop policies that are robust under a range of key assumptions. Future work will develop an equivalent model under micro and macro uncertainty to ensure policies designed are immune to all forms of uncertainty. The main findings imply a more comprehensive approach where all four policies (carbon tax, gas tax, annual grant, and electricity subsidy) are combined is crucial for achieving 100% adoption of electric boilers in the UK. All four policies is more cost-effectiveness compared to individual measures. The optimized policy design generates the demand-pull required to achieve cost parity with the cost of heating with natural gas, thereby reducing electric boiler costs and achieving full adoption by 2033. The carbon tax is identified as a critical lever, starting at £280 per tCO_2 and gradually decreasing, in alignment with international trends. Electricity subsidy, though initially high, stabilizes to support innovators. The study highlights the interaction between policies and the need for robust capital expenditure support for early adopters. Overall, the transition to electric boilers proves more cost-effective and environmentally beneficial, contingent on ongoing grid decarbonisation efforts.

5. Conclusions and future work

As the shift towards decarbonised heat solutions for energy intensive industries gains momentum, the importance of optimisation-based market penetration models in shaping the adoption of cleaner technologies becomes increasingly pivotal. This study has provided valuable insights into the design and effectiveness of four policy interventions in promoting the uptake of electric boilers in the UK's chemical sector. A novel multi period market penetration optimisation model was developed and applied to quantify the impact of carbon tax, electricity subsidy, grant, and gas tax in generating sufficient demand-pull for electric boilers in the UK chemical industry. The objective of the optimisation model is to maximise the market uptake of electric boiler over a 10-year period following two adoption scenarios: s-curve and linear adoption. The optimisation framework can determine the optimal value of the four policies required to reduce the cost of electric boilers and generate sufficient demand-pull to trigger further cost reduction based on experiential learning. The model is applied to a case study of all the heating systems (490 boilers) in the UK chemical industry from 1 MW to 60 MW boilers. Results show that effectively implementing a gas tax, electricity subsidy, annual grant and carbon tax can generate sufficient demand pull to reduce the cost of electric boilers from 30 % to 85 % depending on the boiler size. At 100 % uptake of electric boilers in 2033, the carbon emissions from these 490 technologies reduces by 89 %, which is above the 2035 UK industry goal of 60 % reduction. The policies are designed such a win-win is achieved between government and industry; specifically, revenue from the carbon tax and gas tax is used to support the grant and electricity subsidy thereby achieving cost neutrality for government. Results also show that Linear adoption incurs a marginally lower net cost by 0.5 %. Hence, policy and adoption pathways determination should be simultaneously done. Results validate the role of technology learning in marginally reducing costs and demonstrate how the effective implementation of carbon tax and electricity subsidies can facilitate the adoption of electric boilers. A high carbon price as well as operation and investment incentives are pivotal to provide industry to consider uptake of alternative technology. For further works, the model's robustness could be enhanced by incorporating uncertainties across all parameters, resulting in designing policy packages under uncertainty resulting in a robust multi period mixed integer non-linear market penetration model. The model's versatility will also be enhanced by applying it to other alternative technologies and fuels.

CRediT authorship contribution statement

Devan Nilesh Patel: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Resources, Software, Visualization, Writing – original draft. **Pauline Matalon:** Conceptualization, Formal analysis, Investigation, Methodology, Resources, Software, Validation, Writing – original draft. **Gbemi Oluleye:** Conceptualization, Data curation, Investigation, Methodology, Resources, Supervision, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

All data shared in the manuscript and the model made open source with a link provided in the appendix.

Supplementary Information

The data for all the cases examined in this paper, as well as the python code, is made available on GitHub: https://github.com/Devan05/Electric-Boiler-Multiperiod.

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