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A SYSTEM DYNAMICS APPROACH TO ASSESS THE IMPACT OF POLICY INTERVENTIONS ON THE MARKET PENETRATION OF MICRO GAS TURBINES

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ABSTRACT

Decentralized power generating systems, such as micro-gas turbines (MGT) for micro combined heat and power (CHP), can contribute to achieving the global energy and emission targets thanks to features like low emissions, primary energy savings, and fuel flexibility. It can also help increase the share of renewables due to its ability to easily integrate with renewable energy systems. Micro gas turbines, despite being such a promising technology, have achieved very limited market success due to barriers like high investment costs and a lack of supporting policies. The large-scale market penetration of MGT requires clear and strong policy support to achieve widespread adoption.

This paper establishes a quantitative model to assess the impact of the policy measures on the long-term market penetration of MGT for the domestic micro-CHP to establish a relationship between policy parameters, economic factors, technological advancements, and the market share of MGT.

The work compares five different policy scenarios for the case study of the UK market. The results demonstrate that the usual economic forces are insufficient for MGT to achieve its long-term market growth. Several combinations of direct and indirect policies are to be implemented by the regulatory authorities to promote the commercial growth of the technology. Finally, some insight into policy and decision-making in the UK for micro-CHP is provided, indicating promising policies to pursue.

Keywords: micro gas turbine, combined heat and power, energy policy, system dynamics.

NOMENCLATURE

ABM	Agent-Based Modelling
BAS	Business as Usual
CCL	Climate Change Levy
CfD	Contract for Difference
CHP	Combined Heat and Power
CLD	Casual Loop Diagram
DES	Decentralized Energy systems
ECA	Enhanced Capital allowances
FIT	Feed in Tariff
GT	Gas Turbine
h	Hour
IC	Investment coefficient
kg	Kilogram
kWe	Kilowatt of Electric Power
kWh	Kilowatt Hour
MGT	Micro Gas Turbine
O&M	Operation and Maintenance
PES	Primary energy savings
PR	Progression ratio
RES	Renewable Energy Sources
RHI	Renewable Heat Incentive
RO	Renewable Obligation
R&D	Research and Development
SFD	Stock and Flow Diagram
SD	Systems Dynamics
TCI	Total Cost of ICE
TCM	Total Cost of MGT
WTI	Willingness to invest

1. INTRODUCTION

The multiple shocks due to the global COVID-19 pandemic and the current Geo-political issues caused significant disruptions to energy systems. These crises have affected energy security, affordability, and sustainability, including climate change's negative consequences [1]. To avoid dangerous climate change, a long-term goal to limit global warming well below 2˚C, preferably to 1.5˚C, compared to pre-industrial levels is set under the first-ever universal, legally binding global climate change agreement called the Paris agreement [2]–[4]. The EU's targets are in line with the global climate actions, which are to be climate-neutral by 2050: an economy with net-zero greenhouse gas emissions with intermediate reductions to 55% of their 1990 levels by 2030 [5]. To achieve these climate change targets and energy security, there is a requirement for the effective implementation of renewable energy sources (RES), increased energy efficiency improvements, and carbon capture and storage [6]

In the above context, decentralized energy systems (DES) can easily find their place over a traditional centralized generation system in the energy system, as DES can increase the security of supply, reduce transmission losses, and lower carbon emissions [7]. DES can further help to increase the contribution from renewables due to its integration with RES. Available low-carbon commercial systems, such as small-scale combined heat and power (CHP), can reduce greenhouse gas emissions and ensure energy security compared to a separate supply.

Micro gas turbines for combined heat and power are one of the emerging technologies that can contribute to meeting the targets with characteristics like low emissions and fuel flexibility. MGT is also one of the most reliable technologies for the integration of renewables in different configurations [1]. MGT has undergone numerous technological advancements over time, as the total CHP efficiency of MGT has almost doubled [2]. Later, far more gradual advancements were made to the MGT technology, which covers control, component design, combustor, recuperator, rotor layout, and other areas [3].

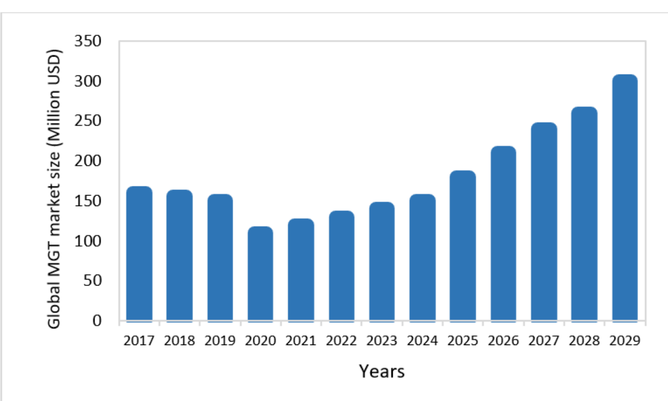

FIGURE 1: FORECASTED GLOBAL MARKET SIZE OF MGT

Because of these advancements in MGT research and development, the global market for MGT has been growing until 2020. This growth was put on a hold due to the coronavirus which resulted in declining demand for MGT and their parts due to the overall declining demand for energy. But the market growth of MGT is still forecasted to reach 286 million USD in 2029 by Fortune Business insight as shown in FIGURE 1. The major driving factors for the expected growth are the growing electricity demand in general and the increment in overall CHP market share, which is driven by the energy and environmental agendas in most of the countries.

MGT, despite being such a promising technology, has been long enough in the market to have achieved this limited market success due to economic barriers and a lack of supporting policies. MGT financial difficulties are primarily due to its high initial cost and reciprocating engines being significantly less expensive [4], [5]. MGT has several advantages over ICE, such as lower emissions, a low maintenance cycle due to fewer moving parts, and a low operation and maintenance costs [6]–[8]. The summary of the comprehensive comparisons of ICE, MGT, GT, and the fuel cell is presented in Tables 1 and 2 [7], [9]–[11]. It is to be noted that the fact sheet provides average values of the performance characteristics and does not intend to represent a specific product.

Previous research suggests that the adoption of micro-CHP technologies includes an interplay between incentive policies, technological advancement, and consumer behaviors [12]. For MGT to be widely adopted, there needs to be strong and explicit policy backing on a large scale. Though MGT can easily find its position due to the global policies in various countries supporting RES and CHP [13], [14], there is still a need for direct policies for MGT to expedite its growth.

This paper develops a quantitative model to assess the long-term impact of policy measures on MGT market penetration for the micro-CHP application. This framework uses a system dynamics (SD) approach, which is capable of handling highly dynamic and complex issues involving interacting feedback loops. The SD model establishes a relationship between policy parameters, economic factors, consumer behavior, technological advancements, and the market share of MGT. The parts and subsystems of the methodology have been adapted from various literature to create a global SD model for MGTs market penetration [15]–[19]. Policy support can be divided into two types: direct policy support and indirect policy support. Four scenarios based on different policy combinations are considered: business as usual; direct policy; indirect policy; and both direct and indirect policy. The categorization of these scenarios is based on previous research on the development of electric vehicles under policy incentives [17]. The sensitivity analysis is also used to determine the leverage point(s) of the market share of MGT. The findings presented in this paper are based on a case study of the UK market, but this model can be used to study MGT market penetration in any country. Several combinations of direct and indirect policies are to be implemented by the regulatory authorities to promote the commercial growth of the technology.

Technology	ICE	MGT
Size Range (kW)	5 - 10,000	30 - 330
Electric Efficiency (%)	27-41	25 -35
Overall/Global Efficiency (%)	77-83	63-72
Typical Power to heat ratio	0.5-1.2	0.5-0.8
Part Load	Ok	Ok
Installed Cost (Capital, Shipping & Installation)($/kWe)	1500-2900	2500-4300
Cost O&M (¢/kWh) (without fuel)	0.9-2.5	0.9-1.3
Operational Life of MGT system(estimation) (h)	30000-60000	40000-80000
Emissions NOx(kg/MWh)	0.03 rich burn 3 wat cat., 0.0025 0.4 lean burn	0.06-.2

TABLE 1: TECHNICAL CHARACTERISTICS DATA FOR THE DEFINED RANGE OF ICE & MGT [7], [9]–[11]

Technology	GT	Fuel cell
Size Range (kW)	500 - several thousands	May-00
Electric Efficiency (%)	24-36	30-63
Overall/Global Efficiency (%)	65-71	55-80
Typical Power to heat ratio	0.6-1.1	1.0 - 2.0
Part Load	Poor	Good
Installed Cost (Capital, Shipping & Installation)($/kWe)	1200-3300	5000-6500
Cost O&M (¢/kWh) (without fuel)	0.9-2.5	0.9-2.5
Operational Life of MGT system(estimation) (h)	30000-60000	30000-60000
Emissions NOx(kg/MWh)	0.2-0.6	0.001-0.002

TABLE 2: TECHNICAL CHARACTERISTICS DATA FOR THE DEFINED RANGE OF GT & FUEL CELL [7], [9]–[11]

This paper is structured as follows: Section 2 provides the technical, economical, and policy background for MGT, and the simplified global SD model is defined along with its subsystem descriptions; Section 3 presents the main results of our market shares of MGT based on simulations of different policy scenarios for MGT; and Section 4 includes the conclusion of the work and the scope of future development.

2 MATERIALS AND METHODS

When analyzing the impact of energy policies on the deployment of micro gas turbines, we should choose a modelling technique that can be applied to a complex and dynamic system. First of all, the system is complex, as the factors affecting the deployment of the technology are quite interrelated. Numerous feedback loops in the system contribute to the rate of deployment, which makes the system complex. The second characteristic of the deployment of such technology is the factors related to the adoption rate and changes in the policies, which tend to change over time and are hence mostly endogenous to the system, which makes the system's behavior unpredictable and dynamic.

A wide range of research has been conducted to find the best modelling technique. Two major modelling techniques are appropriate for modelling such systems: agent-based modelling (ABM) and system dynamics (SD). ABM is the most suitable method to use when enough information about the individual behavior of agents is known. Whereas, at the individual agent level, very little knowledge is available in terms of the rate of deployment of any technology. SD seems to be most suitable for this type of system, as in SD modelling, individual agents are taken out of consideration and global system behavior is defined [18].

SD was developed at MIT Sloan in the 1950s by Professor Emeritus Jay W. Forrester to analyze complex social science behaviors. Today, SD is used in a wide range of areas, including policy evaluation [20]. The SD approach is one method for understanding and managing the relationships between different parts of a system and how those relationships influence the overall system's behavior over time. The process of system dynamics modelling begins with the formulation of a problem, which determines the system's boundary, and is followed by the formulation of a dynamic hypothesis, the formulation of a simulation model, testing, and finally policy design and evaluation [18]. The computer model of system dynamics allows us to better understand and analyze the system and its structure. This model and its understanding could be used to design and evaluate policy changes. The SD simulation is done with the code VENSIM [21].

Technology Data	MGT 1	MGT 2	MGT 3
Rated Electric Power (kW)	200	250	333
Net Electric Power (kW)	190	242	323
Electric Efficiency (%)	28.4	26.1	28.7
Overall Efficiency (%)	66.3	64	70.2
Typical Power to heat ratio	0.75	0.69	0.69
Installed Cost ($/kWe)	3150	2700	2560
Cost O&M (¢/kWh)	1.6	1.2	0.8
Operational Life time (h)	40,000	40000	40000
Emissions CO2(lbs/MWh)	0.4	0.24	0.22
Emissions NOx(lbs/MWh)	739	804	668

TABLE 3: TECHNICAL AND ECONOMICS DATA OF MGT PRODUCTS [22]

2.1 Technical and Economic Background

In this study, the target market for the technology industrial and commercial buildings, we limit our analysis to MGTs units ranging in size from 100-500 kWe. This range considers all the

MGTs except lower than 100kWe due to its variations in application which will change the policy scenarios.

The current model of MGT is using methane (natural gas) as fuel but MGTs can run on various fuels such as kerosene, including renewable fuels like biofuels, hydrogen and so on. The MGT technical, cost and emissions data of the available technologies is taken from Combined Heat and Power Technology Fact Sheet Seri used in the model. It is stated that technical and economic data are average values of the products that existed in the industry, despite the fact that they do not represent a particular product [22]. Table 3 shows the data used in this model.

2.2 The Systems Dynamics Model

We apply the SD modelling technique here to simulate MGTs market penetration. The Global system dynamic model consists of five major subsystems: Bass diffusion, learning by doing, technology cost (MGT and ICE), investment, and R&D. The model covers the period 2020-2030.

2.2.1 The Global Systems Dynamics model

The framework of the model consists of a combination of a stack and flow diagram (SFD) and casual loop diagram (CFD). The Global system dynamics model in Figure 2 Shows the SFD of the MGT units deployed. The SFD establishes the relationships between the different variables, the stock in the rectangle box shows the accumulation of the no. of units installed with some initial value. The flow shown by the arrow changes a stock over time. The arrows indicate the interaction between the different variables, some of these include feedback loops. Creating a flow diagram is an essential step in SD modelling, and the relationship between variables is established by a series of differential equations. There are also the positive and negative loops formed by the feedbacks.

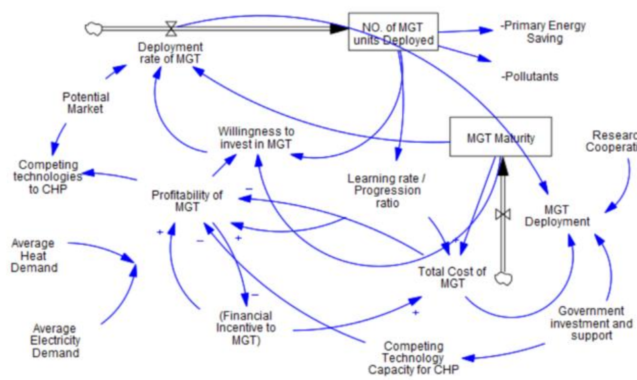

FIGURE 2: SIMPLIFIED GLOBAL SD MODEL

2.2.2 Bass Diffusion Subsystem

The base diffusion model overcomes the startup problem in the logistics models of innovation diffusion. The bass diffusion model describes the process of how current adopters and potential adopters of a newly developed product interact [16]. The rate of total adoptions is the sum of adoption resulting from imitation and advertisement [18], [23]. The total adoption rate is the summation of the adoption from the word of mouth and through the advertisement rate.

The Bass diffusion subsystem is shown in Figure 3. The yearly increment rate of MGT installation through advertisement and imitation is given by the set of following equations [18], [19].

$$AR = aP + ciPA/T \quad (1)$$

$$T = P + A \quad (2)$$

Where AR is the total rate of increase of the adopters (units/year), a is the advertisement effectiveness (units/year), P is the potential adopters (units/year), c is the contact rate (1/year), I is the probability of adoption (dimensionless), A is the number of adopters of technology, and T is the total number of units. The value for the Parameters a and c is assumed based on the power generation technologies values from the literature.

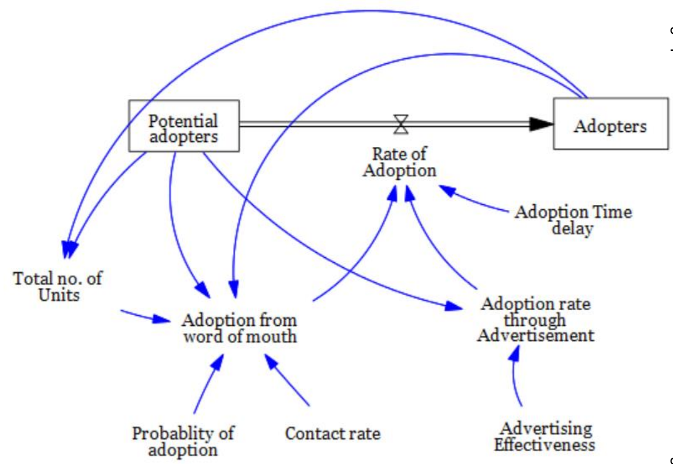

FIGURE 3: BASS DIFFUSION SUBSYSTEM

2.2.3 Learning by doing

The prices of the products drop over time with the maturity of the product due to factors like "learning by doing." Learning/Experience curves are a method of quantifying long-term cost reduction as a function of total production or usage of technology [24].

For the deployment of MGT, this model takes into account the learning curve in terms of Unit Installed and O&M cost of MGT. Figure 4 shows the effect of learning by doing on the installed unit cost, the same has been applied to other costs. The following formula often illustrates the unit cost decline with cumulative production [15]:

$$C_{CUM} = C_{\circ}.CUM^{b} \quad (3)$$

Where C_{CUM} is the cost per unit, C_o is the cost of the first units produced, CUM^b is the cumulative production of MGT, and b is the experience index. The relative cost reduction (1 - 2^b) is calculated by the experience index for each doubling of cumulative production. The value of the progression ratio used to define the cost reduction for different technologies is shown by equation 4 [18].

$$PR = 2^{\mathrm{b}} \quad (4)$$

The values of the PR have been used in the range of 70-90% with respect to energy generation technologies [24].

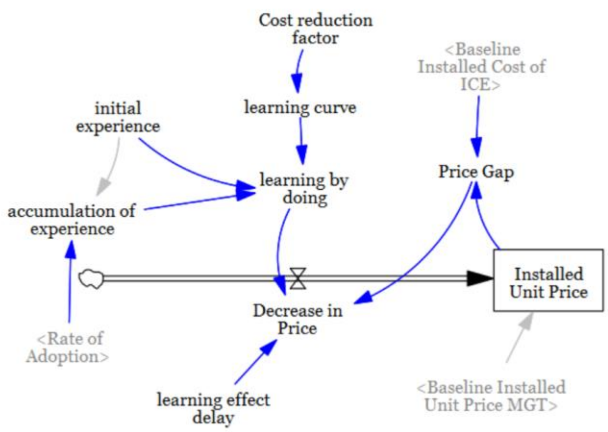

FIGURE 4: LEARNING BY DOING SUBSYSTEM

2.2.4 MGT and ICE Cost

In this subsystem, we are calculating the total cost of MGT during its entire lifetime. The total cost is calculated using four major costs: total installed cost (capital cost + shipping cost); O&M cost; fuel cost; and electricity reselling cost. The flow diagram of the MGT cost is shown in Figure 4. The data for the unit cost of MGT has been mentioned in Table 1. The gas and electricity prices and their forecast are taken from the BEIS prediction based on 2019 which doesn't take the effect of current inflation.

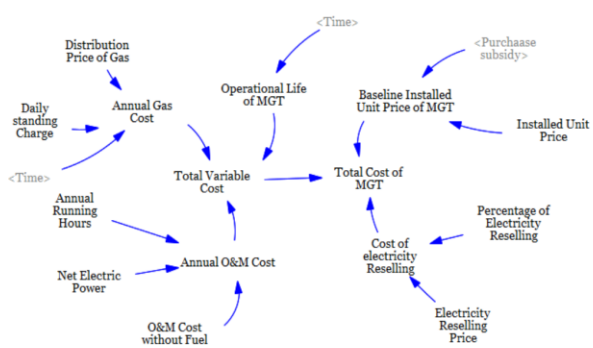

FIGURE 5: TECHNOLOGY COST SUBSYSTEM

Similarly, because ICE is the main competitor of MGT in the CHP market, we calculate the total cost of ICE here. We are neglecting other competitors (sterling engines, SOFC, and many more) here by keeping the model more generalized. The total cost of ICE is calculated in the same way as the MGT cost and has a similar flow diagram [24].

2.2.5 Investment system

In this subsystem, we calculate the investment and the total amount of installed MGT and ICE based on the very important factor, willingness to invest (WTI). WTI denotes the willingness to invest in MGT for CHP applications by manufacturers and businesses [17], [25]. Due to the limited scope of this paper, the equation does not take into account the other factors affecting willingness to invest, such as consumer awareness, and accessibility of services related to technology. The equation used in the model is based on the relative total cost difference of ICE and MGT. The value of WTI is assigned based on the TCI and TCM. In general it is assumed that there will be more investment in MGT if TCI is far more than TCM, and vice versa.

$$WTI = \begin{cases} 1, & TCI > 1.5 * TCM \\ 0.75, & 1.2 * TCM < TCI < 1.5 * TCM \\ 0.5, & TCM < TCI < 1.2 * TCM \\ 0.25, & TCI < TCM \end{cases} \quad (5)$$

2.2.6 Research & Development

This subsystem develops the relationship between MGT innovation, government and industry support, the total cost of MGT, and policy support from the government for example Government subsidy shown in this flow diagram. The stock and flow diagram of the R&D subsystem is shown in Figure 6. The gap between the target and the actual value of the units being deployed each year determines the investment coefficient (IC). IC can be depicted by the series of nested if functions [26].

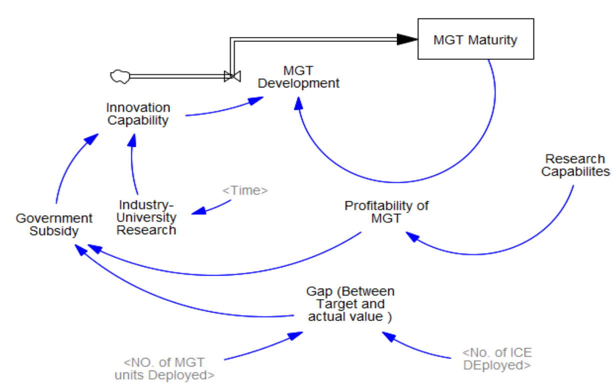

FIGURE 5: RESEARCH AND DEVELOPMENT SUBSYSTEM

2.3 Model Validation

To test the reliability of the SD model we have done two validity tests first is the boundary accuracy and the structural validity test was done based on the data provided in Table 1 [27]. The other verification is done on the UK's historical data of CHP (from the year 2011-2021), the actual data for the total no of CHP schemes are published by the Department for Business, Energy & Industrial Strategy (BEIS) for verification [28]. According to previous research, the results are typically regarded as satisfactory if the simulation error is less than 10% [29]. The maximum error between the simulated outcomes and the real value of the variable is 8.4%, as seen in Fig. 6. The outcomes of the reality test demonstrate that the SD model is remarkably consistent with the current circumstances. As a result, we think the SD model is solid and capable of capturing the causal linkages between all variables.

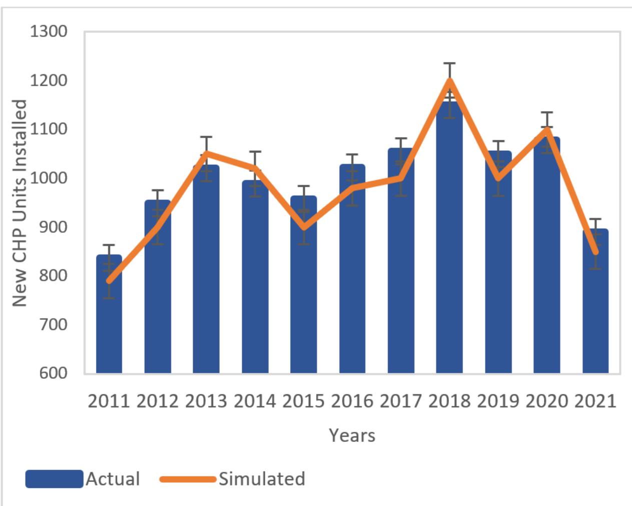

FIGURE 6: SD MODEL VALIDATION

3 RESULTS AND DISCUSSION

3.1 Policy Measures

In this section, we looked at the policy scenarios for the case study of the UK. We hope to learn more about the model's applicability and the dynamics of the MGT market penetration system by using this model. We also aim to learn the implications of different policies and regulations on MGT adoption and market penetration.

The case study will be run on five different combinations of policies, business as usual, direct policy, indirect policy, and both direct and indirect policy.

There are no direct policies favouring any specific technology for CHP based on its advantages, but there are general policies supporting CHP in the UK similar to other countries. A government program called CHPQA evaluates and certifies the effectiveness of CHP in the UK. CHPQA was implemented in 2001 in accordance with the UK energy-efficiency strategy and EU Directive 2012/27/EU on energy efficiency [30]. Most of the direct financial support is given to the CHPQA-certified good-quality CHP [31]. Good quality CHP is exempt from the Climate Change Levy (CCL), which is a non-domestic tax on the gas and electricity consumed [32]. Good quality CHP also had the benefit of Enhanced Capital Allowances (ECA), which have phased out after 2020. There is also additional support for the renewable-fueled CHP, which is now closed for new units, but CHPs already under the Renewable Obligation (RO) continue to receive support for up to 20 years from the date of their accreditation. Contracts for Difference (CfD) have taken over as the primary mechanism for assisting new large-scale low-carbon power generation since the RO was closed to new applicants. Climate Change Agreement (CCA), a voluntarily signed pact by UK businesses to cut back on energy use and carbon emissions, has several CHP systems installed on its covered properties. Operators are compensated for any qualified energy used at the facilities where a CCA is held by receiving a discount on the CCL [33]. At the conclusion of the transition period on December 31, 2020, the UK ceased participation in the EU ETS, and on January 1, 2021, a UK Emissions Trading Scheme (UK ETS) took its place. The plan was created by the four governments of the UK in order to boost the carbon pricing policy's climate ambition while preserving the competitiveness of UK businesses. The UK ETS will be applicable to sectors like aviation, power generation, and industries that use a lot of energy [34].

There are indirect support in terms of policies, schemes, and acts favouring the integration of renewables and CHP technologies like MGT [35]. A micro-CHP can be used to power generators up to 50 kW under the microgeneration certification scheme. Renewals Obligation Order Feed-In Tariff (ROO-FIT) rates are also available for power generation up to 5 MW. Furthermore, renewable electricity is not taxed according to the Carbon Price Floor mechanism. A fixed-amount incentive for 20 years benefits both domestic and external renewable heat production (up to 23.36 Euro cents per kWh).

3.2 Results

The simulation results were obtained from the SD modelling of the four scenarios for the period 2020–2030. The total amount of MGT during 2020–2030 is shown in Figure 7. It is clearly shown that the lowest possible growth is in the BAS scenario by the end of 2030, as it is already established that there is not enough policy support for the MGT. The gradual increment in the number of MGT in BAS is due to other slow-growing factors like the learning curve, advertisement, etc. On the other hand, the cases with different policy support show a higher amount of MGT installed by 2030. There is also a substantial difference between the outcomes of direct and indirect support. This is due to the lower CO2 and NOx emissions, which provide an advantage over ICE for the indirect support scenarios, as the direct support for CHP the will be same for both.

The total amount of ICE is shown in Fig. 8. It is clearly seen that the best scenario for ICE is the BAS due to the high investment cost of MGT, whereas the number is lower for the policy support as the policy support is based on the reduced emissions from primary energy savings.

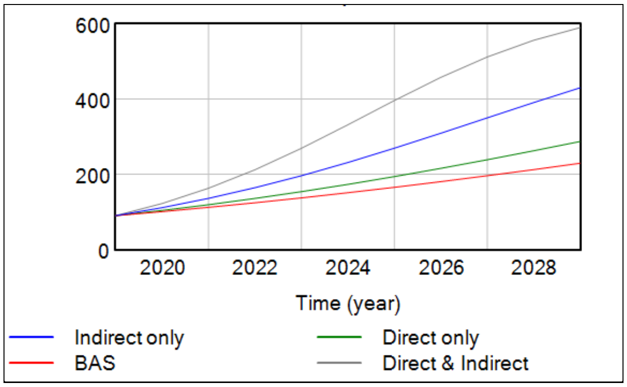

FIGURE 7: TOTAL AMOUNT OF MGT INSTALLED

The total amount of ICE is shown in Fig. 8. It is clearly seen that the best scenario for ICE is the BAS due to the high investment cost of MGT, whereas the number is lower for the policy support as the policy support is based on the reduced emissions from primary energy savings.

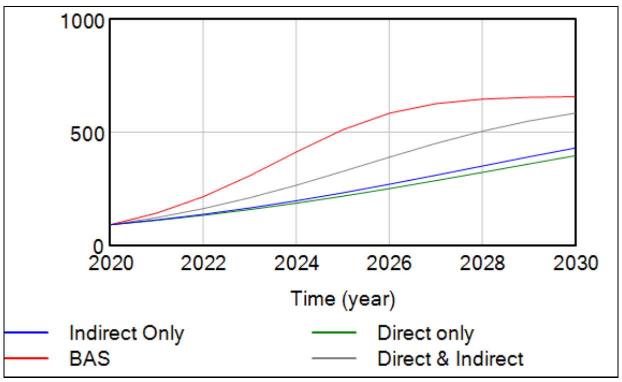

FIGURE 8: TOTAL AMOUNT OF ICE INSTALLED

This result is due to multiple factors which lead to favor the MGT technology over ICE for the CHP application based on the support provided such as willingness to invest in MGT has increased due to the reduced initial outlay cost of the MGT with the help of financial and investment support by the government. The ICE couldn't keep up based on its disadvantages of more NOx and CO2 emissions that restricted their support from the government.

Sensitivity analysis is crucial for examining how the results change depending on the different important parameters. However it is inevitable that there would be some subjectivity in parameter setting. The sensitivity analysis is performed for the subsidy over 6 years with a 20% value and the electricity reselling factor in the current UK market. It seems that using both grid-repurchased electricity and investment subsidies may not be more effective, as seen in Figure 9. This is due to the size of the units and their applications in industrial and commercial buildings, which does not leave enough electricity to sell, and also due to the lower electricity reselling factor.

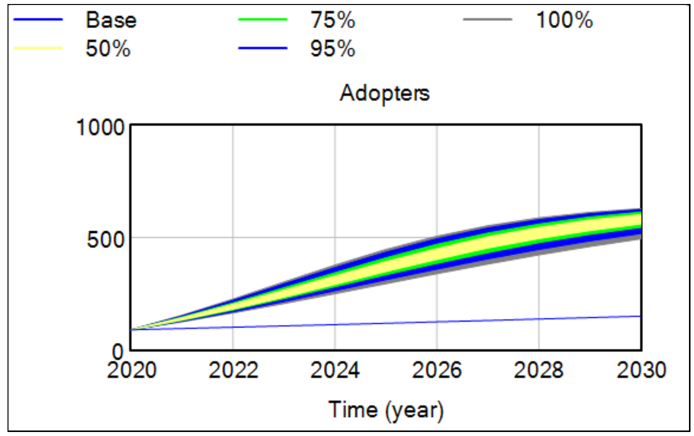

FIGURE 9: SENSITIVITY ANALYSIS FOR SUBSIDY OVER YEARS & ELECTRICITY RESELLING

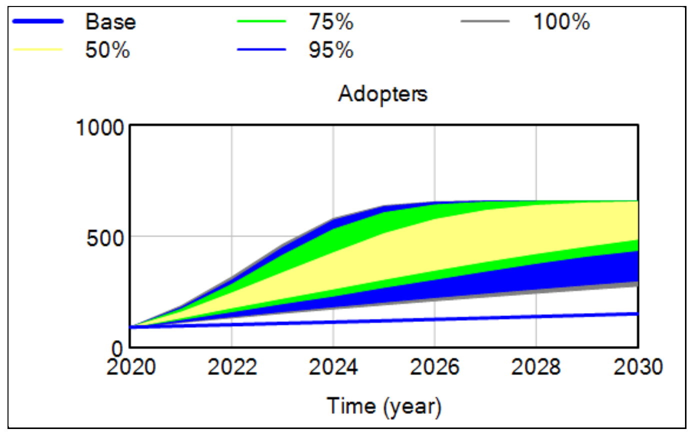

FIGURE 10: SENSITIVITY ANALYSIS FOR R&D AND FINANCIAL SUPPORT

The last sensitivity analysis is done for the cooperative policy instrument, which consists of R&D and financial support (demonstration projects). The support for the R&D is provided during the initial years in order to expedite the growth of the MGT. The financial support provided to the manufacturer also helps in reducing the price for the consumer by offsetting the initial outlay costs. It can be seen that these factors have a huge impact on the market growth of MGT due to the high impact of the innovation capabilities on the technology development and its maturity over the long run.

Net present value and Payback period is also calculated for the MGT-2 based of the data available. It can be clearly seen that the payback period has almost reduced to half with both the policy support.

	BAS	Both Direct and Indirect Policy
NPV	1,188,897	14,657,877
Payback (Years)	21	9

TABLE 4: NPV AND PAYBACK PERIODS OF MGT 2

4 CONCLUSION

Micro gas turbines that are used in CHP applications has proved to be a promising technology for high-efficiency Decentralized energy conversion with easy renewable integration. The main concern when it comes to the wide spread market penetration is the ability to maintain performance while minimizing the initial outlay costs.

In this paper, a quantitative model is developed that can be used for a thorough understanding of the MGT market penetration issue and to explore the impact of policy interventions based on the different policy combinations. The results clearly demonstrate that without the assistance of Policy and regulatory framework, such technology will probably not be able to evolve widely. This is due to the high initial cost, which serves as a significant entry barrier to the technology. Long-term market penetration requires the combination of both direct and indirect policies. The major findings in this paper is that in order to expedite the market penetration of MGT, the support on both supply side and demand side is required along with the consumer awareness.

Along with the policy support for the technology there is an ongoing requirement for the technological advancement of the MGT to compete with ICE and sustain in the market. Other renewable fuels and energy sources can be considered for future work due to the benefits of MGT, such as fuel flexibility and easy integration with RES. MGT can thus benefit from the policy support provided to renewables.

This paper seeks to bridge the gap between the actual impacts of policy support for low-carbon technologies and to contribute to the growing need to assess the broad impacts of potential policy implementation, as well as to assist researchers and policymakers in better understanding and formulating long-term policies.

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