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Modelling governance for a successful electricity sector decarbonisation

Elsa Barazza, Pei-Hao Li, Neil Strachan *

UCL Energy Institute, University College London, 14 Upper Woburn Place, London WC1H 0NN, UK



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ABSTRACT

Early and deep electricity decarbonisation is critical to achieve the overall energy transition target of net-zero emissions by 2050. This paper extends an electricity agent based model to capture the inter-dependence of consistent governance with underpinning societal pressure and resultant investment strategies. Results show only with the strongest level of governance – reflected in the range of national/local policy mechanisms used, and their strength/timing when interim targets are met/missed – can near-zero electricity emissions be met well before 2050. Strong governance can also ensure a stable electricity system, with consistent policies mitigating the intensity of any investment cycles. Strong governance entails higher capital investments, but these can deliver lower electricity prices in the long-term. And strong governance means that a successful electricity decarbonisation does not need to be built solely on existing incumbents, but also via local cooperatives to aggregate household financing and demand side management. However, with inconsistent governance, a vicious cycle ensues with a weak rationale to enact ambitious policies at both the local and national levels, significant inertia in new electricity investments, and hence “failure” scenarios of decarbonisation. This challenges the prior findings of optimistic achievement of electricity decarbonisation scenarios by standard techno-economic optimisation models.

1. Introduction

1.1. Critical role of electricity decarbonisation

To contribute to global mitigation of climate change and meet the climate change reduction targets set out in the Paris Agreement, the UK was the first G20 economy to legislate a net-zero greenhouse gas (GHG) emissions target by 2050. To achieve this ambitious long-term target, the Climate Change Committee (CCC) requires under the 6th carbon budget to reduce UK emissions by 78 % by 2035 relative to 1990 [1].

Similar to almost all developed countries, the energy sector is responsible for the majority of UK GHG emissions – with electricity production specifically accounting for 15.4 % of total GHGs in the UK in 2020 [2]. Low-carbon sources produced 54 % of total UK's electricity in 2021, with renewables accounting for 40 % [3]. As impressive as this progress has been, renewables' share was still lower than the share of generation from fossil fuels (43 %). The critical role of the electricity sector in overall energy systems decarbonisation has been well demonstrated [4] as the key to enable zero carbon end-use sectors – notably road transport, residential heating and industrial processes [1]. Hence a full and early decarbonisation of the electricity sector is an essential

requisite to meet the UK's (and other country's) long-term climate mitigation goals.

However, a compete electricity decarbonisation is a huge policy challenge entailing very large investments in low-carbon technologies. As a technology-specific example, the UK Government has committed to quadruple offshore wind installed capacity by 2030 [5]. More broadly, the CCC estimated that annual investments of GBP 50 billion per year between 2030 and 2050 in low-carbon technologies and infrastructure will be needed (across electricity plus buildings and transport) in the UK to successfully achieve net-zero by 2050 [1]. The UK investment landscape in renewable assets is diverse and comprises incumbent utilities, new-entrants (e.g. project developers and institutional investors) and local players (e.g. municipal utilities, community energy and households). All these actors have different risk and return requirements [6], and different investment strategies and motivations for investing in renewable technologies [7].

Delivering this electricity sector transition requires recognition of the inter-related complexity of society, governance and investment. It is no longer sufficient to simply assume strong and consistent governance as in the large majority of prior electricity and energy system models. These studies generally assume a single decision maker who enacts and

* Corresponding author.

E-mail address: n.strachan@ucl.ac.uk (N. Strachan).<https://doi.org/10.1016/j.erss.2023.103240>

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then consistently maintains a set of policies [8].

National Grid's Future Energy Scenarios (FES) are a high profile example of how electricity transition modelling has normally been done. FES scenarios [9], start with a stakeholder process for key assumptions which are then fed into an energy system optimisation model (UK TIMES), linked to a dispatch model (BID3) for operational electricity sector analysis. Hence the focus is overwhelmingly on the techno-economic characteristics of the transition (technologies, fuel costs, flexibility, system balancing) with the goal to minimise costs. Neither investor and governance agents' diversity nor the political dimension is accounted for in such an optimisation approach [9]. And looking internationally, the great majority of country decarbonisation pathway studies primarily focus on technology and economic uncertainties [10].

1.2. Contribution and layout of paper

This modelling paper directly challenges the prior findings of standard techno-economic models and studies (such as UK National Grid FES scenarios [9]) that generally find electricity decarbonisation can be successfully achieved. The novelty of this paper is to take the insights on consistent governance from the political economy [11] and the socio-technical transition [12] literatures, and translate them to enhance an agent based model (ABM) to capture different governance arrangements. This study extends BRAIN-Energy [13,14], an ABM of UK electricity sector generation and investment, to focus on the different governance arrangements (captured in the rate/direction of societal drivers, the resulting consistency in decisions of the governance agents, and the subsequent investment decisions of the different types of investors). This ABM approach is applied to test the high-profile UK National Grid FES scenarios [9], to better assess their realism and their key uncertainties.

This paper is structured as follows: Section 2 gives a literature review of both conceptual and modelling papers to highlight the existing research gap on analysing the governance of electricity sector decarbonisation. Section 3 gives the key details of the BRAIN-Energy ABM model – extended to better capture governance of the electricity transition. Section 4 presents the reimplementation and testing of the FES scenarios, with a set of key results presented in Section 5 to test if and how they meet (or do not meet) zero emissions by 2050. Finally, Section 6 draws out the main conclusions and policy implications.

2. Literature review

2.1. The complexity of the electricity system transition

A set of widely cited conceptual approaches in socio-technical transition studies highlight that to ensure that any electricity transition is successful and sustainable, this implies changes across the technical, social, political, institutional and economic spheres. These conceptual approaches include the multi-level perspective [15], the co-evolutionary framework [16], and transformative environmental policy [17]. As practitioners try to move these – mostly theoretical and qualitative – approaches into practical policy evidence tools [18], they highlight the importance of considering:

- a) how societal drivers underpin policy [19],
- b) how politics and governance maintain policy [11,12], and
- c) how multiple actors implement policy [20].

As regards to societal change; a key challenge in reaching zero emissions will be to understand how to unlock energy-intensive behaviours, consumption patterns based on fossil fuels, and high-carbon investments [21]. To achieve this, consumers should be not conceptualised as passive energy users, but rather as active stakeholders who develop new social routines for energy use, provide investment flows and support new business models [22].

As regards to the institutional dimension; the political economy literature argues that good governance is essential to achieve a sustainable and successful energy transition [23]. These authors also highlight that different actors respond differently to policies and regulations, and hence successful governance should be based on a clear understanding of the links between policy and practice change in the energy sector. To this end, Schaffrin et al. [24] introduce the concept of “policy output”, which refers to the “actions” of governments, and to their choices to change or keep the current legislative conditions. The main changes which a policy should bring about to be durable include creating a supportive institutional environment, and achieving “policy feedback”; which includes transforming the preferences and practices of the population and hence altering changing their investments [25]. Providing supporting institutions can survive political pressures when specific constituencies are impacted, a policy can become deeply rooted and hard to dismantle [11].

Real world examples of failure of energy policy durability include declining levels of political support in the UK when moving from emission reduction target setting to the actual implementation of stringent policies to achieve this [26], and in the dismantling of renewable energy policies in Spain and the Czech Republic when they adversely affected the broader political economy of the electricity sector [27]. Millar et al. [28] goes further in a Canadian analysis which shows how framing by advocacy coalitions made the difference in a sustained phase out of coal vs difficulties in maintaining renewables feed-in tariffs or emission cap-and-trade programs.

As regards to multiple actors; the range of stakeholders involved in the energy transition is ever increasing [29]. Historically, incumbent utilities have been major investors in the electricity sector, but there is a growing debate about their ability to respond to disruptive forces such as decarbonisation and decentralisation [30]. Incumbents have been seen as potentially slowing down and obstructing change and transition [31], including lobbying government to shape power markets to their continuing benefit [32]. Incumbents however, continue to play a major potential role in providing the required scale of future low-carbon investment [33]. Local investors (e.g. households, community groups) are another key player in the facilitation of the electricity transition. This can entail early investments in decentralised renewable energy assets [34], as well as subsequent scale-up of smart local energy systems with communities partnering with government and private investors [35]. All these actors have different risk-return considerations when investing in renewable assets, and while incumbents may be more driven by economic motivations, local actors can be more driven by wider socio-environmental considerations [36].

2.2. Modelling the electricity sector

The majority of existing electricity system models focus on techno-economic aspects and solve using optimisation techniques [37]. Such models, generally assume fully rational, utility-maximising and homogeneous actors [38], treat societal and governance dimensions as exogenous [29], and are hence unable to represent co-evolving dimensions (technological, political and social) in the electricity transition [14]. As conventional models do not do this, they have been shown to incorrectly capture real-world transitions [37], as they omit societal or governance inertia [39]. Ongoing efforts to improve electricity/energy optimisation models continue to focus on technological details including improved spatial and temporal representations [40] – i.e. improving their strengths rather than addressing their weaknesses.

As detailed in Section 2.1, both sustained societal pressure and resultant policy coalitions (national and local) are required to maintain a virtuous cycle to deliver a long-term transition [11,29]. This will require consistency in the policy framework, in order to ensure that both consumers and firms are actively involved in taking low-carbon choices, and that the transition is fair, affordable and secure.

Agent-based models (ABMs) can offer a significant improvement in

realistic assessments of meeting such ambitious decarbonisation targets. ABMs are bottom-up simulation models where agents are the main unit of analysis [41], which interact with each other considering their own characteristics and decision rules, and their expectation of other market actor strategies [42]. These models can thus represent complex investment behaviour, and hence capture the interactions and co-evolution which take place between the technological, political and social dimensions of the energy sector transition [43]. A key challenge in employing ABMs is to ensure that they still retain a decent representation of the technical and operational aspects of an electricity system in terms of diurnal and spatial matching of supply and demand [44].

Previous ABM studies in the electricity sector mainly focused on long-term decarbonisation pathways where national electricity producers are key agents [18,45], and also studied national electricity generators' investments under different policy conditions [46]. Furthermore, within the electricity sector, ABMs have been applied to investigate how capacity markets and flexibility options can influence long-term decarbonisation [47], and to assess the necessity of introducing electricity storage and other flexibility options in an electricity market with a capacity market [48].

More recently ABMs started to incorporate social drivers through the preferences and actions of local actors including households and communities in an attempt to include energy consumption and demand changes [49]. Examples include understanding barriers which local actors face in the development of district heating [36] and cooperatives to scale up smart local energy systems [35] to achieve net-zero emissions by 2050. Broader societal shifts including incorporating cultural resistance to change and the diffusion of environmental values have been investigated [50]. However societal change remains still quite under-explored in ABMs, with only a subset of ABM studies studying the complexity of consumer behaviour in the energy sector [49], and of these most are focused on the transport as opposed to the electricity sector [51].

In all these ABMs, however, governance is still generally treated as exogenous.

2.3. Incorporating governance into agent-based modelling (ABM) of the electricity sector

There is a clear research gap in the fuller incorporation of governance in electricity sector ABMs. A review of 61 ABMs [52] found only 7 of these encompassed governance agents. Some of these ABMs focused primarily on the interplays between different government organisations [53], while others only looked at the interplay between public support and governance actors [54]. Earlier version of the BRAIN-Energy ABM [13,14] used in this study, focused primarily on the interplay between policy and investor actor strategies. An exploratory model [55] did cover the full narrative of social drivers through governance actions through to investor decisions, but only in a stylised treatment.

A political economy definition [11] of good governance policy has: strength (hopefully increasing), consistency (i.e. continuous), responsiveness (doubling down on set-backs) and collaboration (national and local). To achieve this in the long-term challenge of electricity sector decarbonisation requires an integrated modelling treatment of societal pressure, consistent governance and sustained investment by actors, to hence enable policy durability [11]. Without this integrated view the viability of advocacy coalitions for a virtuous cycle of low carbon technology investment and hence electricity system transition will not be maintained [28]. Potential infeasibilities have been shown in a range of transition scenarios [56], and are likely to apply to modelling outputs as well.

This study aims to explore this possibility by extending BRAIN-Energy, an electricity sector ABM, which is extended to model governance arrangements – underpinned by levels of societal engagement and resulting in very different investor decisions.

3. Methodology

3.1. BRAIN-Energy agent based model

BRAIN-Energy (Bounded Rationality Agents Investment model), is a UK electricity sector agent-based model [13,14]. For this study, the previous version of BRAIN-Energy [57] was updated; including extending the modelling horizon from 2050 to 2070 to allow all existing and new investments to be replaced in the market, and including new local investors called “cooperatives” [35].

BRAIN-Energy is calibrated to 2012 as a base year to validate the model against historical data. The exogenous data sources for the main calibration variables in BRAIN-Energy, cover:

- Annual UK electricity demand projections [1]
- Historic national half hourly electricity demand data for load profiles [9]
- Fuel cost projections for natural gas and coal [57]
- Capital costs projections for electricity technologies [58]
- Operational & maintenance (O&M) cost projections for electricity technologies [58]

The temporal resolution has been refined to eight time-slices in a year (i.e. 4 time-slices in a typical day in two seasons), with electricity loads at the evening peak time-slice scaled up by a capacity factor to reflect possible fluctuations of electricity demand on extreme days. A stylised spatial representation of the UK electricity market is divided into three regions based on their different renewable energy potential and governance structures. The three regions are London (with a dense population, high solar PV potential and mayoral powers), Scotland (with high potentials for onshore and offshore wind power and an executive government), and the rest of UK to allow further diffusion of renewable energy technologies.

As discussed in Section 3.2, the agents explicitly mimic the UK's government institutions, and the policy mechanisms mimic the actual policies employed and proposed in the UK. To apply such an ABM approach to other countries would require the capture of nationally specific governance institutions and policies, as done in past work when applying BRAIN-Energy to the UK, Germany and Italy [14].

The model's yearly simulation procedure over the modelling horizon is briefly explained in Appendix A which also includes a flow diagram of the model's operation. Full details about the functioning of BRAIN-Energy can be found in [19,20,35,59], with equations and data in the model documentation [60] covering power system operation, agents' characteristics, economic criteria for investment, and demand-side responses.

3.2. Agents in BRAIN-Energy

There are two main types of agents in BRAIN-Energy: investor agents (Table 1) and governance agents (Table 2).

Investor agents are divided into national investors (incumbent utilities and new-entrants) and local investors (households, local suppliers and renewable energy cooperatives). On top of being different types of organisations, investors have different financial endowments, a different cost of capital and different risk-return considerations. Investor agents take investment decisions based on their net present value (NPV) calculation of future investment options, and their myopic expectations of future prices. The investment decisions of the investor agents are also affected by self-learning (from their own past investments) and by imitation of other investors' successful strategies, hence by learning from the others. This set of mechanisms (see Appendix A) in investors' decisions leads to non-optimal choices.

The newly-introduced renewable energy cooperatives, allow households to aggregate their investments in renewable energy plants, thus acting like community ownership models and facilitating the growth of

Table 1
Investor agents in BRAIN-Energy.

Investor agents	Region and number	Technology
National	Incumbent utility 2 national agents	All: nuclear, gas, biomass, solar PV, onshore-and offshore wind
	New-entrant 2 national agents	Renewable energy only: biomass, solar PV, onshore-and offshore wind
Local	Municipal utility 1 in London region, 1 in Scotland region, 1 in the rest of UK region	<ul style="list-style-type: none"> London: solar PV Scotland and the rest of UK: biomass, solar PV, onshore and offshore wind
	Household 1 in London region, 1 in Scotland region, 1 in the rest of UK region	<ul style="list-style-type: none"> London: solar PV Scotland and the rest of UK: solar PV and onshore wind
	Renewable energy cooperative 1 in London region, 1 in Scotland region, 1 in the rest of UK region	Renewable energy only: biomass, solar PV, onshore wind

Table 2
Governance agents in BRAIN-Energy.

Governance agents	Region, number & aim	Policy instrument
National government	1 national agent. Aim: to decarbonise the UK power sector, by encouraging new investments in renewable energy plants.	CO ₂ price Contracts for Difference (CfDs) for RE technologies
Regulator	1 national agent. Aim: to promote security of supply by encouraging investments in gas and nuclear power plants	Capacity market: to promote security of supply by encouraging investments in gas and nuclear
Local government	3 local government agents (one in each region). Aim: to decarbonise local region.	Subsidises to renewable energy investments in their own region

local renewables [35]. What differs between renewable energy cooperatives and the other local investors in BRAIN-Energy is the fact that, if successful, cooperatives can extend their investments beyond their local region. To do that, they can access subsidies provided by the national government and can also access loans at low rates established by the government. This agent focuses on households rather than other small-scale public/commercial operations as the 28 million relatively homogeneous homes in the UK represent a very significant share of UK electricity consumption.

Governance agents in BRAIN-Energy comprise the national government, local governments and the regulator (Table 2). They all have different strategies, and use different policy mechanisms to incentivise investments in renewable energy generation plants and reduce CO₂ emissions from the UK electricity sector, and to guarantee a stable and secure supply of electricity at all times.

The interaction between the governance agents and the investor agents in BRAIN-Energy happens through the policy mechanisms. Policy mechanisms shape the investment choices of the investors, as well as the revenues which the investors are able to cumulate from their power plants through time. In turn, the investment choices of the investors shape the structure of the market, which then prompt the governance agents to adjust their policy mechanisms. This co-evolution of the policy dimension with the investment dimension is explained in Appendix A and in [14].

For this paper, the specific settings of the strategies of the investor

and governance agents in the different scenarios are explained in Tables 3a, 3b and in Section 4.2.

4. Scenarios of governance of the electricity transition

4.1. Optimisation approach to National Grid's Future Energy Scenarios (FES)

As discussed in Section 1, National Grid's Future Energy Scenarios (FES) are a high profile example of how electricity transition modelling has normally been done [9]. A strength of the FES scenarios is the transparent and iterative stakeholder review exercise, with final assumptions, consistent with those used for UK government scenarios [1]. This assumption set is then taken into an energy system optimisation model (UK TIMES) that assumes exogenous societal drivers, idealised governance and a single decision maker. This focus on the techno-economic characteristics of the transition (costs, technologies, system balancing) is cemented by linking UK TIMES to a dispatch model (BID3) for detailed operational electricity sector analysis.

The FES scenario framework is graded by the speed of decarbonisation and the level of societal change. Falling Short (FS) is the continuation of current trends and policies with minimal behavioural change. System Transformation (ST) has a supply-led approach to decarbonisation with rapid uptake of new electricity generation technologies, electricity systems and infrastructure flexibility, and deployment of hydrogen. Consumer Transformation (CT) has a demand-led approach to decarbonisation with consumers being willing to change behaviour, demand flexibility and high uptake of energy efficiency. Leading the Way (LW) combines the supply- and demand-side elements of ST and CT respectively. All scenarios meet security of supply standards across electricity and other fuels, for all years, seasons and diurnal periods.

Such a techno-economic approach leads to striking conclusions on the optimistic achievement of net zero emissions in the electricity sector. LW goes zero electricity emissions in 2033, with ST and CT in 2034 and even FS achieving this in 2047. As UK TIMES is a full energy systems model (adding industry, buildings and transport to the electricity and upstream sectors), the UK's overall net zero GHG emission target [5] is met in 2047 in LW, and in 2050 in both ST and CT. Even in FS, emissions are reduced by 80 % (relative to 1990 levels) by 2050.

4.2. Implementation of FES scenarios in BRAIN-Energy

This paper uses this well-known, transparent and stakeholder-driven FES scenario set [9], as a benchmark to explicitly model governance levels for electricity decarbonisation. First, the energy price and technology cost assumptions in the BRAIN-Energy ABM are calibrated to FES inputs. Second, to focus on the different governance arrangements, a distinct implementation narrative is employed via:

- the rate/direction of societal drivers,
- the resulting consistency in decisions of the governance agents,
- the subsequent investment decisions of the different types of investors.

The way in which the increasing level of societal change underpins the decisions of the governance agents in BRAIN-Energy across the 4 scenarios is captured in the increasing ambition to reach zero emissions at 2050 – reflected in the policy mechanisms used, their strength and timing, technologies covered, capital available for subsidies and how the governance agents revise policies in case of success or failure (Table 3a). Governance agents then interact (via policies which influence the market) with investor agents who have individual decision rules and responses to experiences in low-carbon investments (Table 3b). In turn, the outcomes of the investment decisions shape the market; hence governance agents' policy decisions are based on evidence and policy

Table 3a
Governance settings in the 4 scenarios.

		Falling Short (FS)	System Transformation (ST)	Consumer Transformation (CT)	Leading the Way (LW)
Governance agents	National gov.	Low <ul style="list-style-type: none"> • CO₂ price: not revised if interim targets not met, up to £100/mt between 2035 and 2070 • Contracts for Differences (CfD): to offshore wind only, auctions take place every 5 years 	Medium <ul style="list-style-type: none"> • CO₂ price: increased 2× if interim targets not met and lowered again when targets met, can be up to £300/mt • CfD: to offshore wind and biomass, auctions take place every 3 years 	Medium <ul style="list-style-type: none"> • CO₂ price: increased 2× if interim targets not met and lowered again when targets met, can be up to £455/mt • CfD: to all RE, auctions take place every 3 years 	High <ul style="list-style-type: none"> • CO₂ price: strong price throughout even when interim targets are met, up to £500/mt between 2035 and 2070 • CfD: to all RE, auctions take place every 2 years
	Regulator	Capital (budget for RE support) Ambition Mechanisms and time	Low <ul style="list-style-type: none"> • Capacity market • Scarcity pricing: no 	Medium <ul style="list-style-type: none"> • Capacity market • Scarcity pricing: electricity price can increase 2× if de-rated capacity margin is negative 	High <ul style="list-style-type: none"> • Capacity market • Scarcity pricing: electricity price can increase 2× if de-rated capacity margin is negative
	Local gov.	Capital (budget for capacity market) Ambition Mechanisms and time	Low N/a	Medium N/a	High <ul style="list-style-type: none"> • Subsidies to local PV investments. Auctions every 3 years until budget is over.
		Capital	N/a	N/a	Limited

Table 3b
Investor settings in the 4 scenarios.

		Falling Short (FS)	System Transformation (ST)	Consumer Transformation (CT)	Leading the Way (LW)
Investor agents	Capital	<ul style="list-style-type: none"> • Incumbents have strong capital • Other national investors (new-entrants) and local investors have low capital 	<ul style="list-style-type: none"> • National investors have strong capital • Local investors low capital 	<ul style="list-style-type: none"> • National + local investors have strong capital 	<ul style="list-style-type: none"> • National + local investors have strong capital
	Cost of capital	High cost of capital for all investors	Cost of capital lower for national investors and higher for local ones	Cost of capital lower for local investors and higher for national ones	Low cost of capital for all investors
	Return on investment in RE (willingness to invest in RE)	All investors: high returns (all investors have low willingness to invest in RE)	<ul style="list-style-type: none"> • National investors: low returns • Local investors: high returns 	<ul style="list-style-type: none"> • Local investors willing to invest in RE, low return required. • National investors low willingness to invest in RE, high returns needed 	All investors: low returns (all investors have high willingness to invest in RE)
	Losses	All investors absorb losses for shorter in RE	National actors absorb losses for longer in RE, local for shorter	Local actors absorb losses for longer in RE, national for shorter	All actors absorb losses for longer in RE
	Self-learning	All investors: <ul style="list-style-type: none"> • Low weight on self-learning for gas plants • High weight on self-learning for RE 	National investors: <ul style="list-style-type: none"> • High weight on self-learning for gas plants • Low weight on self-learning for RE Local investors: <ul style="list-style-type: none"> • High weight on self-learning for RE 	National investors: <ul style="list-style-type: none"> • High weight on self-learning for gas plants • Low weight on self-learning for RE Local investors: <ul style="list-style-type: none"> • Low weight on self-learning for RE 	All investors: <ul style="list-style-type: none"> • High weight on self-learning for gas plants • Low weight on self-learning for RE
	Imitation	No	No	Yes – local investors imitate other local investors' successful investments. The same happens among national investors.	Yes – local investors imitate other local investors' successful investments. The same happens among national investors.
	Renewable energy cooperatives Willingness to participate in DSR	No No DSR	No Low DSR	Yes – households don't lend money Medium DSR	Yes – high willingness from households to lend money High DSR

outcomes in a co-evolutionary process [14]. The range of investors includes societal actors – both households and cooperatives – thus bringing the modelling full circle.

Once overall societal drivers have set the level of decarbonisation

ambition, governance agents revise policies differently in the 4 BRAIN-Energy scenarios according to the realised outcome of these policies. This has been modelled in BRAIN-Energy following the political economy literature [11] that argues if a policy is supported by strong societal

engagement, it becomes deeply rooted and is hard to change. Hence, we define and model consistent governance from this political economy view [11] as: Strength (hopefully increasing), Consistency (i.e. continuous), Responsiveness (doubling down on set-backs) and Collaboration (national and local).

Therefore, in LW scenario, where the government agent is underpinned by high societal pressure, it is able to maintain a very high CO₂ price throughout the years even if interim targets are already met. In ST and CT scenarios, the national government has medium ambition to meet net-zero by 2050. Hence it increases the CO₂ price (respectively by 2× and 3×) if interim CO₂ reduction targets are not met, (i.e., “doubling-down” on policy-failures), however once emissions are in line with targets the national government then lowers the CO₂ price again. Finally, in the FS scenario, with low government ambition and society not engaged, the government only enforces lower CO₂ prices and doesn't revise the price upwards if interim decarbonisation targets are missed. Other national government levers are subsidy investments in renewable energy (RE) through Contracts for Difference (CfD): moving from FS to LW scenario this happens with an increasing budget, increasing frequency of auctions and with a higher number of technologies being eligible. Finally, there is also a gradation of capital provision: in ST there is cheap capital for national players; in CT there is cheap capital for local investors (Table 3a).

The national government has the great majority of energy policy powers, and substantial funding, but is less responsive to societal pressure (e.g., BEIS needs to fight other governmental departments for money and all departments have societal priorities) so it responds with a time lag. For local governments in the UK, more than 300 local authorities have declared “Climate Emergencies” (www.climateemergency.uk/blog/list-of-councils) with targets for 2030, 2050 or both. This indicates a degree of political commitment and responsiveness to local societal ambition to achieve net-zero, and in CT and LW scenarios local governments subsidise local investments in RE. Finally, the regulator also takes a long-term supportive role in meeting emissions targets which is also graded by scenario, while in the short term ensuring stable supply and lowest feasible prices (especially for vulnerable customers).

Investors then react (again with a gradation through the scenarios) with progressively better reaction to the society/policy framing via absorbing short-term losses, self-learning, and imitation of best strategies (Table 3b). The growing ambition of societal change and hence governance strength/consistency is captured from FS to LW scenarios in the increasing willingness to invest in RE, in the underpinning cost of capital, and in the participation of community-ownership models in CT and LW scenarios to which households have an increasing willingness to lend money. Moreover, moving from FS to LW investors have an increasing willingness to absorb losses from RE plants to keep these active. Self-learning (based on past unprofitable investments) and imitation (of other investor's more successful strategies) are also graded by scenario (Table 3b).

It is important to note the difference between the ST “system-led” and CT “community-led” scenarios. In BRAIN-Energy this is reflected through a stronger participation of national investors and centralised generation technologies in ST, underpinned by cheaper cost of capital for national-scale investors. In ST scenario it is the national government driving the transition, while local governments are not actively involved. In contrast, the CT scenario is characterised by a stronger participation of local investors (including community-ownership models), underpinned by cheaper capital for these types of investors and by active, responsive and ambitious local governments. The stronger level of societal change in CT scenario is also reflected in the households' participation in demand side response (DSR), while households don't take part in DSR in ST scenario (Table 3b).

5. Results and discussion

The results from the 4 scenarios implemented in BRAIN-Energy show

how different strengths of governance, underpinned by a different level of societal change and co-evolving with investor strategies, can lead to radically different UK electricity sector decarbonisation pathways. The model reveals how different level of governance impact:

1. the evolution of CO₂ emission reductions and development of renewable technologies
2. the stability of the UK electricity system
3. the cost of the transition
4. how investor market shares evolve through time

5.1. Evolution of CO₂ emissions and development of renewable technologies

LW scenario decarbonises the deepest and the fastest (over 10 years before the other 3 scenarios), with CO₂ emissions near-zero already from 2033 (Fig. 1). This vital for the subsequent timing of transport (electric vehicles) and residential (heat pumps) decarbonisation.

In contrast, the FS scenario can be considered a “failure” scenario as it doesn't meet the CO₂ reduction targets at 2050. Because of the government's low ambition underpinned by low societal engagement, and low willingness to invest in renewables, CO₂ emissions first stagnate and then start increasing again between 2050 and 2070 (Fig. 1). Hence, this result highlights how in the presence of low societal pressure and weak/inconsistent government policy, CO₂ reduction progress can be derailed.

CT and ST scenarios have a similar decarbonisation pathway and can be considered partial failures: each reach zero emissions from the power sector in 2057 (Fig. 1), but this is far too late to play a leading role in the UK's overall net-zero GHG target by 2050.

Fig. 2 shows how the share of electricity produced through renewable energy (RE) develops differently across the 4 scenarios. In LW, total electricity produced through RE reaches 82 % at 2050 and 100 % at 2070. In CT scenario which is more “community-led” the share of electricity produced through RE picks up faster from 2035 and is remains higher through to 2070 compared to ST (Fig. 3), with both scenarios over 80 % RE by the end of the model horizon. What changes between the more “system-led” and the more “community-led” scenarios, is the fact that ST scenario is more reliant on gas at 2050 compared to CT, and decarbonisation is achieved through a combination of RE and nuclear (Fig. 5). In contrast, decarbonisation in CT scenario is mainly achieved through RE, with offshore wind and PV playing a main role (Fig. 5).

5.2. Stability of the UK electricity system

Strong governance is also key also to maintain a stable UK power system, ensuring electricity supply meets demand at all times. All 4 scenarios face challenges in ensuring system stability – brought about by “investment cycles” in the light of a strongly increasing (and rapidly decarbonising) electricity demand towards 2050. All 4 scenarios exhibit “investment cycles” in their de-rated capacity margins (Fig. 3), due to investors' strategies under limited foresight of the future. Investors can over-invest at times when their financial conditions are healthy – these periods correspond to the peaks in de-rated capacity margin. But if investors' investment choices turn out not to be as profitable as expected, it takes longer to restore revenue streams, recover costs and then make new investments – this corresponds to periods when the de-rated capacity margin is low. This effect is most pronounced in the ST scenario as the only one which faces a negative de-rated capacity margin (between 2053 and 2057).

Stronger and more consistent governance can mitigate the intensity of these “investment cycles” (LW scenario in Fig. 4). In contrast, FS scenario investment cycles are the strongest, and are mainly caused by on-and-off gas investments (Fig. 4). As a result of capacity margin subsidies, a lower CO₂ price compared to other scenarios, and less ambitious

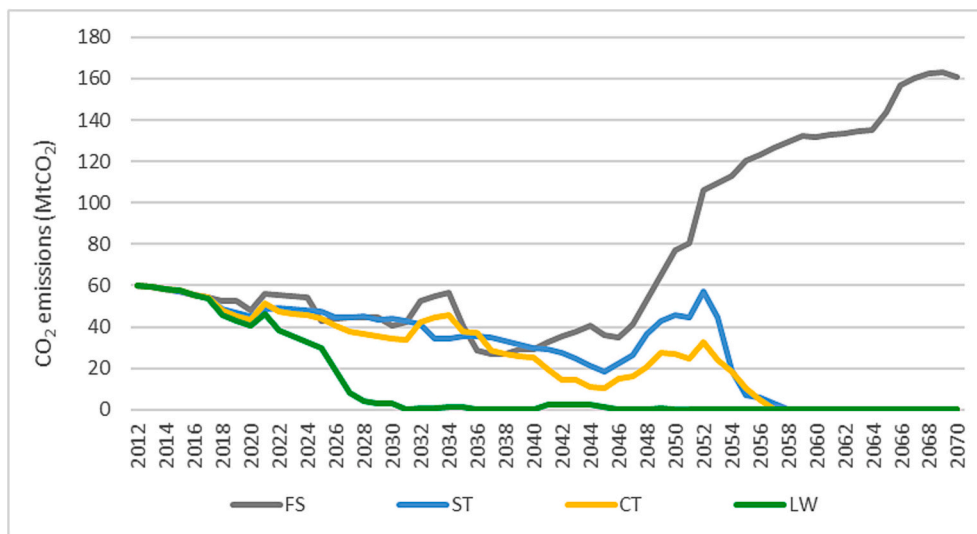


Fig. 1. Evolution of CO₂ emissions from the UK power sector.

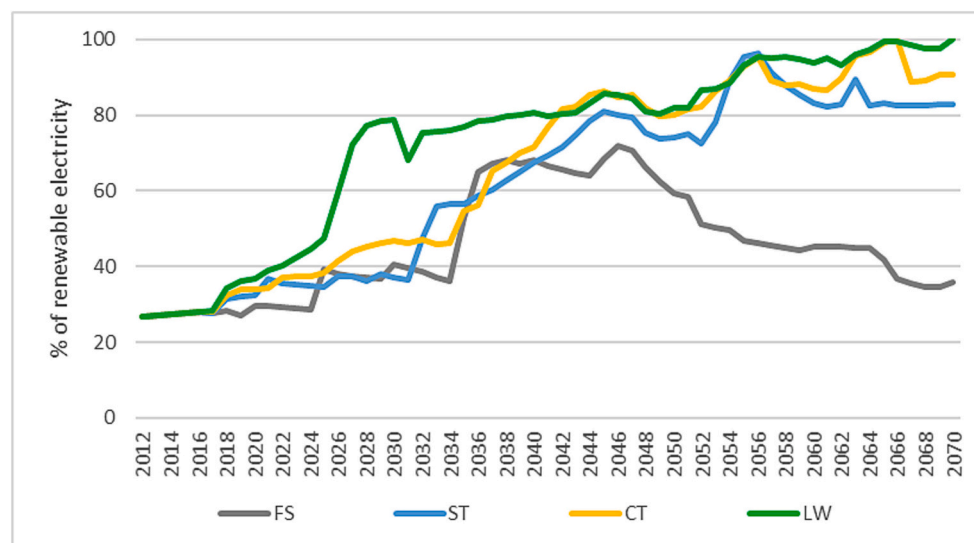


Fig. 2. Share of renewable as % of total electricity production.

CfD mechanism, in FS investors mainly resort to gas investments when new capacity is needed.

CT scenario is more stable compared to the ST scenario and the derated capacity margin is never below zero (Fig. 3). This is due to a combination of stronger policies (stronger capacity market, more CfD subsidies, higher CO₂ price, and local government subsidising local RE with more engaged local investors). The CT scenario benefits from the participation of community-ownership models and households participate in DSR, which leads to less investment under the capacity market in CT compared to ST (Fig. 6), even though the regulator agent is more ambitious in CT. Hence a more “community-led” transition scenario is more effective at maintaining a stable system than a “system-led” one, and achieves that through a lower reliance on capacity market.

Finally, the LW scenario shows no system instability (Fig. 3) between 2012 and 2070, and there is always enough capacity in the system also to satisfy the increasing electricity demand around and after 2050. This occurs even though incumbent utilities become marginal players (Fig. 8) and despite the low electricity price, especially after 2053 (Fig. 7). On the policy side, this is possible thanks to: 1) strongest level of CfD mechanism (highest budget, highest frequency and coverage of all RE

technologies) across the 4 scenarios (Fig. 6), especially during post-2050 low electricity price periods (Fig. 7); 2) active local government with an even higher budget for local RE investments compared to CT scenario; 3) societal engagement enabling government to achieve a strong CO₂ price throughout the transition – maintaining it when interim targets are met and “doubling-down” to increase is when interim targets are not met. This governance stability gives a virtuous cycle with participation of renewable energy cooperatives (who can borrow money from households) and stronger DSR participation by households compared to CT scenario.

5.3. Cost of the electricity transition

Strong governance entails higher capital investment but then enables lower electricity prices.

Overall, the LW scenario has the highest total investment costs (£602bn), 14 % higher than the CT scenario, and much higher (140 %) than the “failure” FS scenario (Fig. 5). Total investments spend is higher in CT vs ST driven by renewable energy. Notably, investments in PV are 163 % higher in CT vs. ST scenario, with the majority of these PV

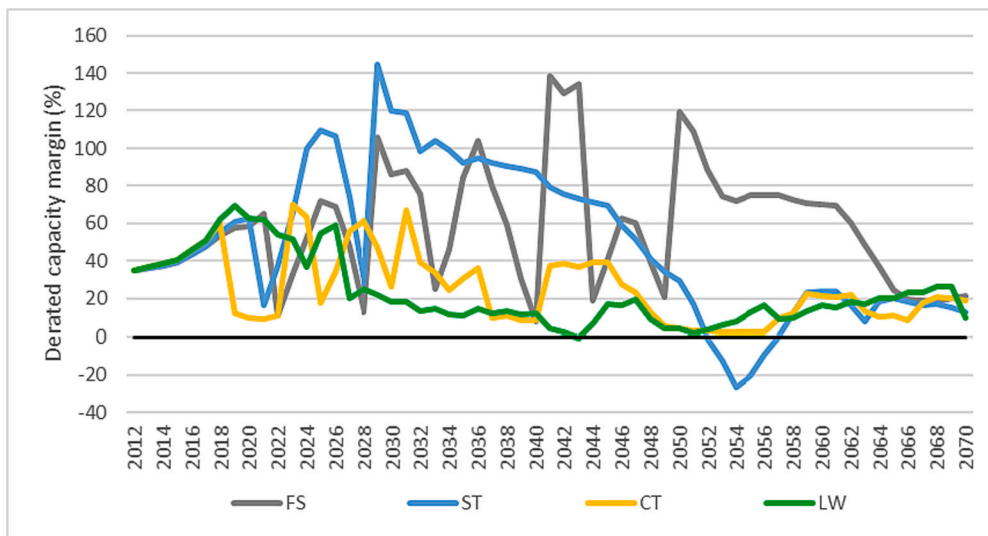


Fig. 3. De-rated capacity margin in the 4 scenarios.

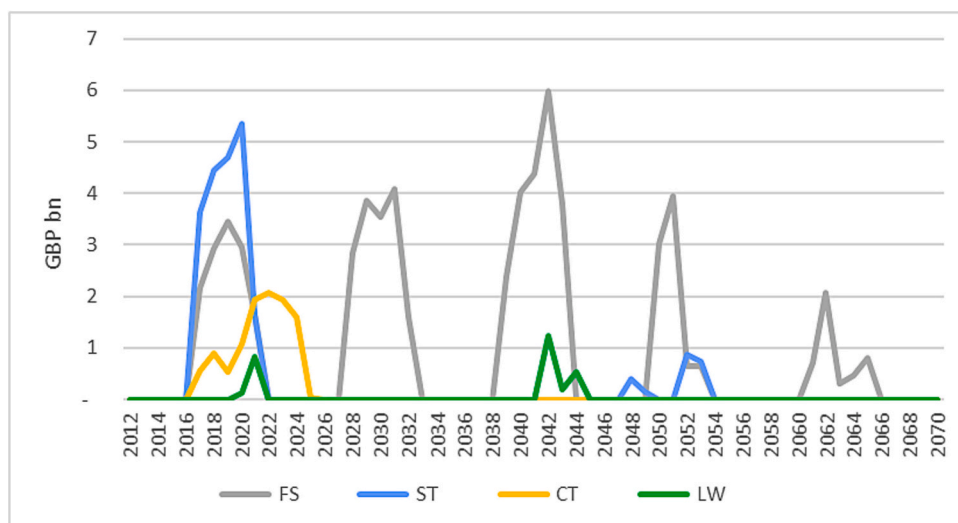


Fig. 4. Yearly gas investments in the 4 scenarios.

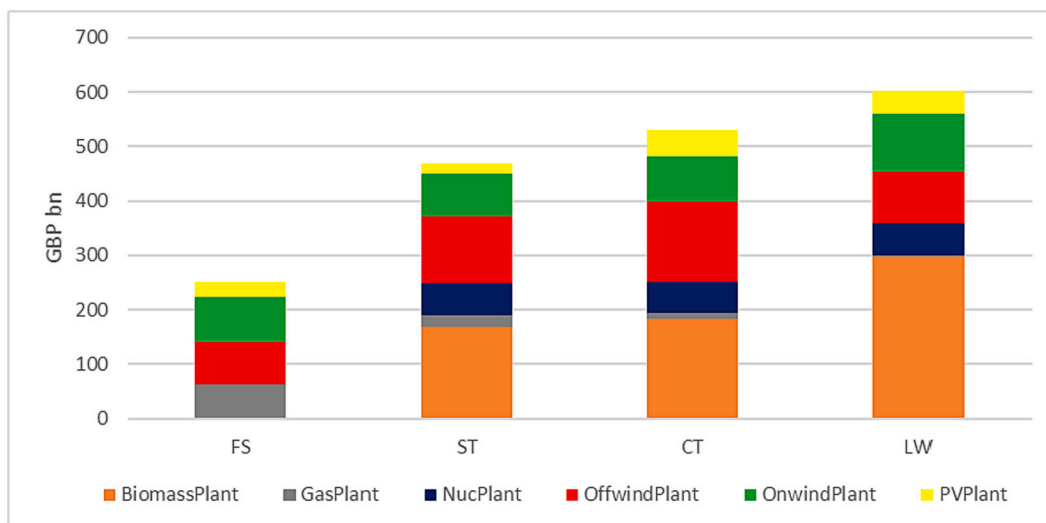


Fig. 5. Total investments by technology in the 4 scenarios from 2012 to 2070.

investments coming from societally engaged local investors. In contrast ST sees higher nuclear (7 %) and gas investments 51 % higher compared to CT (Fig. 5), driven by incumbents being active for an additional decade (as limited learning from past investments makes it harder for incumbents to move away from gas). Fig. 5 also shows how the LW scenario relies heavily on (flexible) biomass plant to achieve both zero emissions and system stability from the UK power system, which raises questions about availability and cost of this biomass resource.

The supporting policy mechanism for this investment spending is very different under weaker/stronger levels of governance (Fig. 6). While in FS and ST scenarios the majority of investments happen under the capacity market, the opposite happens in LW where the majority of investments are in RE and take place under the CfD mechanism. Hence in LW, the significantly higher investment is targeted at steadily building out RE generation as opposed to investing for capacity to ensure stability.

Stronger government can leverage this higher investment to enable lower electricity prices in the long run. The very strong CfD mechanism in LW scenario incentivises investments in RE during periods of low electricity prices, mainly after 2050 (Fig. 7). Combined with the national government maintaining a stable (and high) CO₂ price (supported by societal engagement), RE investments grow more steadily, and “investment cycles” are mitigated (Fig. 7). As a result, the regulator agent doesn't need to increase the electricity price to incentivise investments during times when the de-rated capacity margin is low. In only partially successful transition scenarios (CT and ST) high CO₂ prices impinge on an electricity portfolio that has not yet reduced to near zero emissions, hence raising concern of feasibility in terms of electricity prices, which can climb over GBP 200/MWh. The failure FS scenario exhibits consistently elevated prices.

5.4. Investor market share in response to governance

The investors' market shares in electricity generation (Fig. 8) is a key output from an ABM such as BRAIN-Energy, as it provides an insight which conventional energy system models cannot do. This shows how strong governance means that a successful energy transition does not need to be built on existing incumbents (although they remain an important player).

In FS, incumbents dominate the market, and their business-as-usual strategy in a high emission scenario is even able to erode local investors' aggregated market share (falling from 35 % in 2050, down to only 14 % in 2070). In ST, incumbents are still the majority players but are joined by new-entrants as ambitious government policies to decarbonise the electricity sector are encouraging national players and centralised

technologies. The CT scenario by contrast, has local players (including renewable energy cooperatives), dominate the market eventually reaching 70 % in 2070. This successful growth of local investors in CT scenario is achieved through the early intervention of local government in subsidising local renewable investments (local government is more responsive to societal pressure than national government). This is amplified via strong imitation of successful investments which allow local players to scale up promising strategies.

Finally, the role of local investors occurs faster and extends further in LW. This is the only scenario where households (via cooperatives) are significant players in the future electricity system, and hence show that for cooperatives to become key players it takes a combination of very active and responsive local government investment, plus the national government maintaining a high CO₂ price. The LW scenario achieves rapid reductions in CO₂ emissions (Fig. 1) without compromising the system's stability (Fig. 3), all through the backbone of the electricity system strongly relying on local players (Fig. 8).

6. Conclusions and policy implications

The novelty of this paper is to take the insights on consistent governance from the political economy [11] and the socio-technical transition [12] literatures, and translate them to enhance an agent based model (ABM) to capture different governance arrangements. This ABM approach is applied to test the high-profile UK National Grid FES scenarios of electricity decarbonisation [9], to better assess their realism and their key uncertainties.

This is a vital modelling exercise and in direct contrast to the standard techno-economic optimisation approach (which found the strikingly optimistic achievement of net zero emissions in the electricity sector for all FES 2022 scenarios, with 3 of these scenarios achieving this before 2034). This ABM study paints a picture of a fragile electricity transition with 3 out of 4 scenarios failing to decarbonise electricity quickly enough (or not at all), and hence not able to facilitate broader zero-emissions options in the transport (electric vehicles) and residential (heat pumps) sectors.

The difference between these modelling approaches is in capturing governance as an endogenous and iterative part of the transition. In our ABM approach, strong and consistent governance is reflected in the policy mechanisms used, their strength and timing, the range of technologies covered, capital availability, and how the governance agents revise policies (CO₂ pricing, CfDs, capacity market, subsidies) in case of interim success or failure. This enables both a system and a consumer transformation to meet a net zero compatible pathway (i.e. LW scenario has electricity CO₂ emissions near-zero already from 2033). Strong

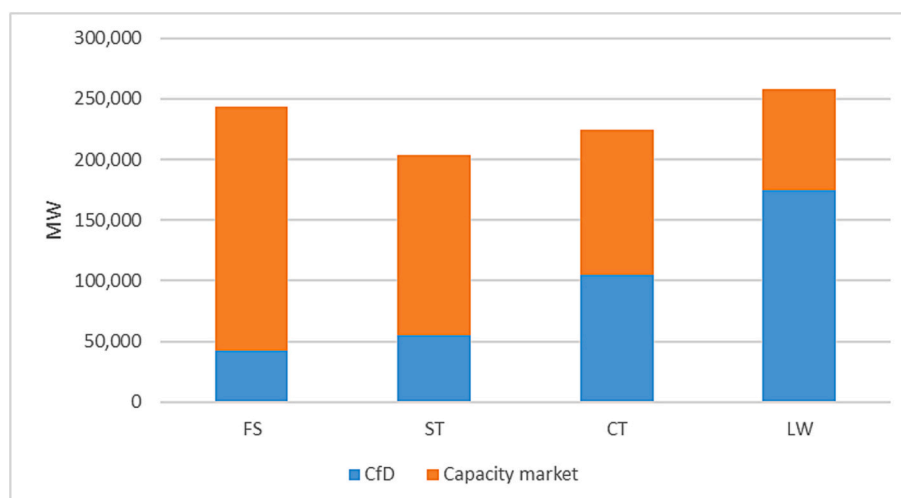


Fig. 6. Total installed capacity (2012–2070) in 4 scenarios.

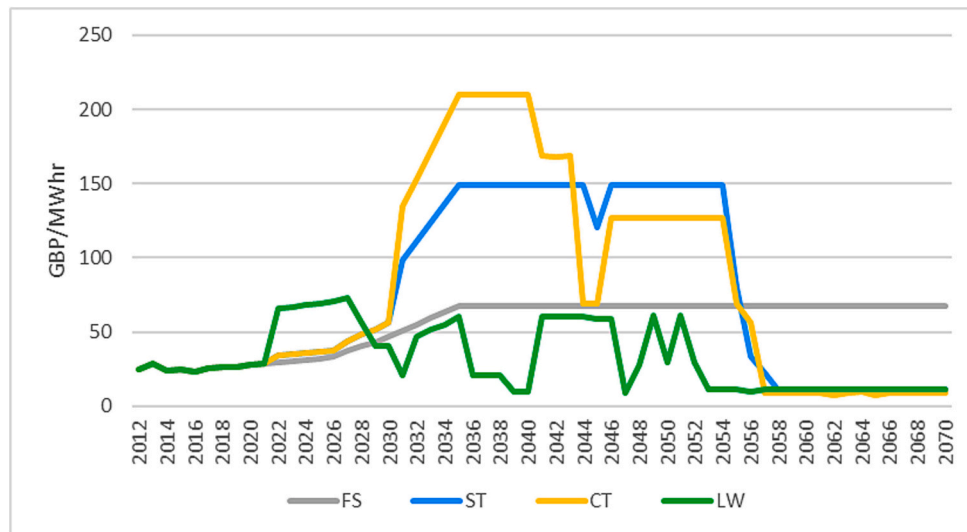


Fig. 7. Yearly electricity price in 4 scenarios.

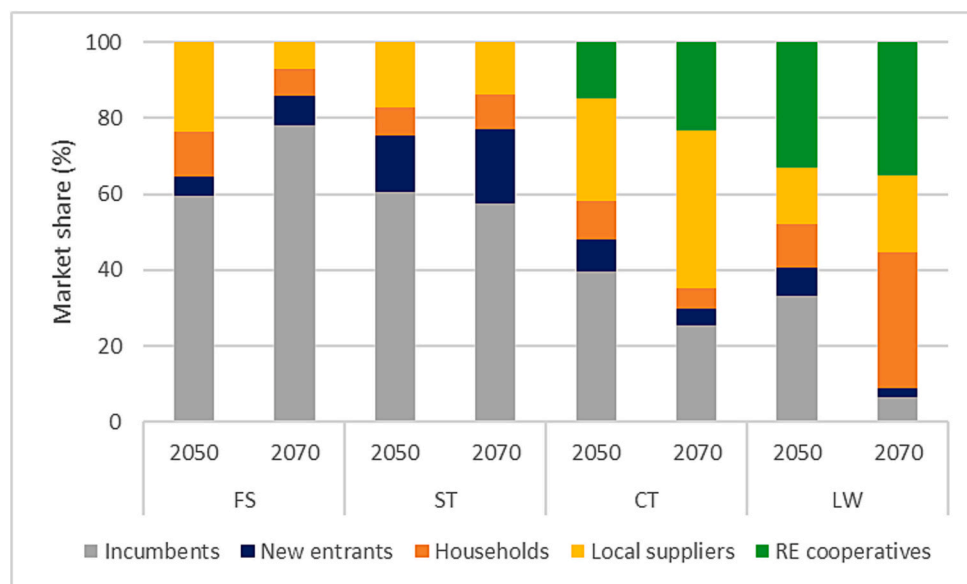


Fig. 8. Investor market share.

governance can also ensure a stable electricity system, with consistent policies (and hence investments in renewable energy) mitigating the intensity of any investment cycles from short-sighted decision making. Last, strong governance means that a successful energy transition does not need to be built on existing incumbents (although they can remain key players) but via the rise of cooperatives to aggregate household borrowing and investment to scale up business models of local generation.

Our study has limitations, as all ABMs conduct a stylized approach for computational reasons. Notably the spatial and diurnal detail of our model is coarse, so our results should be sense-checked by a detailed power system dispatch model with appropriate depiction of spatial supply-demand matching as well as meeting peak capacity requirements. And wider application of this UK-based study to a realistic assessment of other countries' electricity decarbonisation should capture the national and local governance decision makers as well as the specific policies that are politically viable in their own countries – as we have done in this UK study.

But the key insights of this study should be reflected on by policy

makers and investors. As the implementation of the electricity decarbonisation challenges is now well underway, relying on idealised scenarios on what “should happen” is much less helpful than exploring scenarios of what “could happen” under a realistic assessment of how strong governance will be. And as consistent governance is so important, policy-makers should aim to strengthen their ability to maintain policies, through meaningful societal engagement to create a virtuous governance cycle and hence maximise the engagement of a portfolio of investors. This could be done by building consistent support for both supply and demand decarbonisation policies, and basing policies on a review of past achievements [5].

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

Data will be made available on request.

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Appendix A. Model flow of the BRAIN-Energy ABM

To simulate the UK's liberalised electricity market, the BRAIN-Energy agent-based model simulates the operations of the power system, trading in the electricity market, individual investors' behaviours, and policy-makers' interventions sequentially in each model year (Fig. A.1). This procedure repeats iteratively until the target year (e.g. 2050 or 2070) is reached. At the beginning of each year, investors decommission unprofitable power plants and then take short-term operational decisions (electricity production from their stock of assets), followed by bidding electricity into the market at a national and local level. As a result of their electricity sales, the yearly national and local electricity price is created, as well as the electricity supply curve and the CO₂ emissions from the power sector. Based on their electricity sales and the electricity price, investors assess the profitability of their stock of assets and their market share is updated. Investors whose equity is negative exit the market.

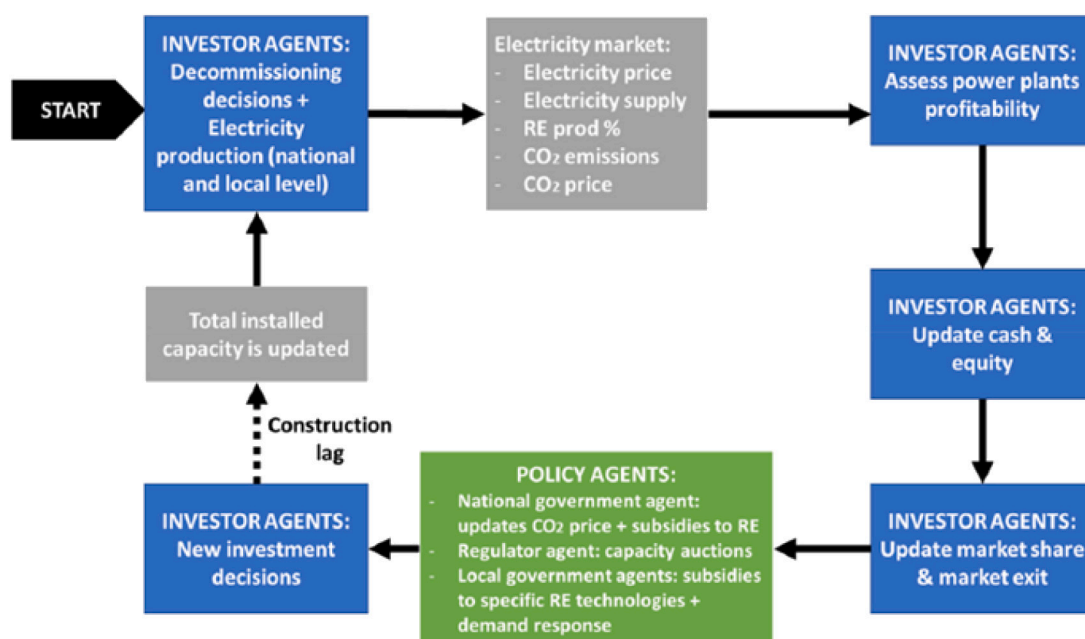


Fig. A.1. Yearly simulation procedure of the model.

Policy agents (i.e. the national government agent, the regulator agent and local government agents) are active in the next step: the national government agent checks the amount of CO₂ emissions (or emission intensity) produced by the power sector at the national level. If the interim decarbonisation targets are not met, the national government agent can adjust the prevailing CO₂ price at the national level. The national government agent also subsidises investments in renewable technologies through Contracts for Difference at the national level. The regulator agent also intervenes in the market to manage eventual supply gaps by enforcing capacity auctions at the national level. Local government agents take the necessary policy measures at the local level (subsidising specific renewable technologies and managing demand response programs). Therefore, the policy changes that the policy agents (the national government, regulator and local government agents) enforce in BRAIN-Energy are endogenous and co-evolve with the emergent techno-economic properties of the sector through the years.

Finally, investors decide about new investments. Newly committed investments start being operational after a planning- and construction lag, and the resulting generation mix is, therefore, an emergent result of the investment and decommissioning decisions of the investors.

For more detailed information, please refer to the model documentation [60]. Note that we have not employed an Overview, Design concepts and Details (ODD) Protocol in this or in prior [13,14,35,59] BRAIN-Energy journal papers owing to the limited availability of guidance on how to use ODD especially for complex ABMs [61].

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