Modelling the socio-political feasibility of energy transition with system dynamics

Keywords

Socio-technical transition, energy systems modelling, energy policy, political capital, social capital, system dynamics

Abstract

A system dynamics model of energy transition, TEMPEST, represents political and societal factors along with energy, emissions and mitigation measures, within a system of feedbacks. TEMPEST simulates energy transition from 1980 to 2080, calibrated to UK historical data. An exogenous uncertainty analysis showed most cases would achieve net zero before 2080, but only 20% would stay within the required carbon budget. Low probability, high impact cases have twice the future cumulative emissions than the best cases. High political capital for energy transition early on would likely reduce total mitigation required, but risks public pushback. Endogenous uncertainty about pushback and new measure difficulty could increase total emissions by a quarter. Dealing with unwanted feedbacks between society and government that reduce political capital will require responsive policy making. The socio-political feasibility of achieving the UK's net zero target is likely less than the techno-economic feasibility estimated through standard energy systems models.

1 Introduction

1.1 The challenge

This paper focuses on the challenge of understanding the whole system, real-world processes involved in transforming a national energy system to emit net zero greenhouse gas emissions by 2050. The need for this is well established. The world '*is facing an unprecedented imperative to rapidly transition to renewable and sustainable energy sources'* (Solomon and Krishna, 2011). At the national level, however, energy transition is only one of many pressing issues faced by governments, and climate change mitigation remains highly influenced by the ever changing world of politics (Meadowcroft, 2009). For example, the phasing out of coal is more possible for governments that are independent and can '*bear substantial political, social and economic costs'* (Jewell et al., 2019).

Governance of energy transition requires numerous types of interventions at different levels of the economy (Smith et al., 2005). The instruments of governance are policy measures, which can be broadly classified into three types: taxes, subsidies, and regulation (Hughes and Urpelainen, 2015). Policy makers may not always have enough influence over policy implementation to ensure expected policy outcomes, however, even when there is good planning (Elmore, 1980). For example: (i) CO_2 emissions reductions from a Czech green investment scheme were 25% lower than expected (Valentová et al., 2019); (ii) environmental regulations do not automatically lead to desired impacts in reduced environmental impacts (Knill et al., 2012); (iii) residential loft and cavity wall insulation measures were found to have reduced fuel use by as little as a third of predicted savings (Wade and Eyre, 2015); two UK competitions for early stage CCS technology development funds were withdrawn without winners between 2007 and 2015; the Green Deal scheme of 2013 (Mallaburn and Eyre, 2012) was cancelled early due to poor take-up[i]..

Part of the difficulty of reliable policy implementation arises from difficulties in evaluating policy outcomes, since evaluation is a vital feedback for policy makers to inform policy learning. For example, making unequivocal conclusions about emissions reductions from transport policies is difficult because the evidence base is not comprehensive (Gross et al., 2009). Evaluators may only be able to assign an improvement in relative terms. For example, thirty years of energy efficiency programmes in IEA countries were found to have accounted for the majority of the decrease in the energy intensity of GDP (Geller et al., 2006). Despite these difficulties, there are many case studies of successful energy transition, such as: the growth of ethanol fuel for transport in Brazil (Meyer et al., 2013); the growth of renewables and the phase out of coal and nuclear in Germany (Kern and Markard, 2016), and the UK's "dash for gas" from coal to natural gas in the power sector (Mallaburn and Eyre, 2012).

1.2 The research gap

Most governments rely on energy systems models for energy transition planning. These models provide sets of possible scenarios and detailed pathways towards decarbonisation. Energy system models are almost all based on techno-economic theory; policies, societal responses to policies, and other factors influencing model outputs are exogenous and determined by scenario definitions. There have been calls for research to improve the level of realism in energy systems models: (i) Deep decarbonisation studies should lead to policy strategies that are '*both cost-effective and sociopolitically feasible'* (Geels et al., 2017), although crucial factors in real-world transitions such as the process of innovation, social acceptance, and political struggles, are difficult to model. (ii) The "dynamic political feasibility space" should be explored, which covers decarbonisation pathways for which all costs, including social and political costs, could realistically be borne (Jewell and Cherp, 2020). (iii) '*The techno-economic, socio-technical and political layers of co-evolution of energy systems should be considered when analysing long-term energy transitions'* (Bolwig et al., 2020). (iv) Insights from social sciences could be integrated into transition models, allowing societal assumptions in existing models to be assessed (Trutnevyte et al., 2019). (v) Although end-use services have been the predominant driver of energy supply expansion, energy systems models focus mostly on energy supply due to the difficulty of modelling future changes in demand (Grubler, 2013).

1.3 Transitions modelling and STET models

The body of work on the theory of modelling transition includes the following: (i) A discussion of models as scenario tools that can be used to inform planning for transition (Malekpour, 2019); (ii) The use of system dynamics modelling and simulation in socio-technical systems transition research (Papachristos, 2019); (iii) Identification of the characteristics of transition modelling, along with its main challenges and approaches (Köhler et al., 2018); and (v) A call to produce robust policy recommendations from models that can identify the intensity, nature and timing of transitions (Papachristos, 2014).

Within the transitions modelling field, there has been a growing trend for socio-technical energy transition (STET) analysis ((Mekhdiev et al., 2018), (Li et al., 2015)). Examples include a transitions model for sustainable mobility (Köhler et al., 2009); a model of technological innovation systems (Walrave and Raven, 2016); socio-technical regime transitions modelling (Papachristos, 2011), a dual-narrative modelling approach of socio-technical transitions, with example application of the historical transition of India's electricity sector (Moallemi et al., 2016); and the Behaviour, Lifestyles and Uncertainty Energy model (Li and Strachan, 2017).

This paper adds to the growing body of STET work. It describes an energy systems transition model called TEMPEST, which models energy, emissions, and political and social factors all together. The paper is organised into sections as follows: Section 2 presents the model conceptualisation, including theories and concepts used; Section 3 describes model development; Section 4 presents the results of an uncertainty analysis; Section 5 discusses the implications of the results and future work; and Section 6 provides conclusions.

2 Model conceptualisation

TEMPEST (Technological EconoMic Political Energy Systems Transition) is a simulation model of the UK's socio-politically driven energy transition. It was built to provide new insights about how real-world national energy transition happens, and to examine the socio-political feasibility of the UK meeting its net zero emissions target by 2050. This section presents an overview of the design of TEMPEST and the concepts used.

2.1 Model overview

2.1.1 Terminology

The following key terminology is used in TEMPEST:

- "Mitigation measures" are any changes that reduce emissions and/or energy consumption. Mitigation measures provide one or more of three types of benefits: (i) Energy supply: new low or zero carbon energy supply capacity that replaces fossil fuel capacity; (ii) Energy demand technologies: improvements in end-use technologies that provide better energy efficiency and/or enabling of low-carbon fuel switching; and (iii) Energy demand behaviours: changes in demand for energy services such as heating, cooling, lighting, and transport of freight.
- "Measure diffusion" is the process by which mitigation measures are developed from early research through to commercialisation, and then adopted throughout society and the energy sector.
- "Policy measures" are governance tools of varying types that are designed to bring about measure diffusion to meet mitigation targets.
- "Theoretical potential" is an estimate of the total potential that each measure could achieve, without considering financial costs, technology build rates, resource availability, or public acceptance.

- "Feasible potential" is an estimate of how much of the theoretical potential is technologically, socially, and economically feasible for implementation.

2.1.2 Modelling method

TEMPEST is a system dynamics (SD) model, built in Vensim. SD allows for the representation of the co-evolution of economy, technology, behavioural, and policy factors over time ((Mekhdiev et al., 2018), (Sterman, 2000)). The use of SD in modelling socio-technical systems and their transitions is well founded (e.g. (Meadows et al., 2005), (de Gooyert et al., 2016); (Papachristos, 2011), (Moallemi et al., 2016)). As a methodology, SD is particularly suitable for achieving the purpose of TEMPEST since it overcomes the limitations of other modelling methods in which '*variables known to be important are ignored because data to estimate parameters are unavailable'* (Sterman, 1994). When such variables are ignored it is the equivalent of saying that they have zero effect, but this is the only value known to be wrong (Forrester, 1961, p57). The model runs from 1980 to 2019 in the historical period and from 2020 to 2080, or the years of reaching net zero, in the future period. The model scope is described in detail in the supplementary information.

2.2 Political and social factors

2.2.1 Political Capital

The concept of political capital (PolCap) is used to represent the political element of energy transition. PolCap acts as a kind of "fuel" or "credit" which can be used to make changes through target setting and policy measures; it has been defined as the potential political power that can be invested in leadership tools such as policy formulation and the overseeing of policy implementation processes (Kjaer, 2013). Setting emissions reductions targets is relatively cheap in terms of PolCap, since targets initially have limited impact on society. Achieving mitigation targets, on the other hand, can be very expensive. Actors across society will be required to make (sometimes unwanted) changes, and investments may become riskier during a period of deep and rapid change.

The existence of co-benefits from policy measures can lessen the PolCap cost. For example, framing energy supply as a security issue allowed more political governance of the UK's energy system (Kuzemko, 2014); mitigation strategies that link improvements in air quality with GHG emissions reductions can increase society's willingness to pay (Jenkins, 2014); the increase in policy abatement ambition after the Paris agreement was partly due to expectations of economic co-benefits from innovation-related technology cost reductions (Schmidt and Sewerin, 2017).

TEMPEST includes PolCap as a stock (a variable that accumulates and depletes) called "PolCap for energy transition". While there is no standard way to measure PolCap, a pattern can be seen when looking at the ups and downs of PolCap in the UK in past decades. Governments tend to hold high PolCap soon after an election, and unpopular policies are often implemented during this time rather than closer to a coming election, to avoid losing votes. Events/trends that can sustain PolCap throughout a government's term include an improved economy and increased national standing in the world; events/trends that can reduce PolCap include poor government response to geopolitical shocks, policies that fail or are seen as money wasters, and strategies that aim to achieve difficult but necessary changes without sufficient public consent. PolCap is needed to deal with all of the pressing issues of government, thus the PolCap available for energy transition will be some share of the total available.

2.2.2 Policy ambition

Policy ambition can be seen as the level of commitment of resources by government, through policies and accompanying budgets to support their implementation. Policy measures are measured in model units of "policy ambition" for energy and emissions savings, and are assigned at the level of mitigation measures. Available PolCap is spent on creating policy ambition, according to the need for mitigation and the amount of PolCap available. When no PolCap is available, no new policy ambition can be added. This aligns with two examples: The Ontario government had insufficient political capital to carry out electricity market reform despite the energy utility Ontario Hydro being close to bankruptcy during the 1990s (Rosenbloom and Meadowcroft, 2014); although strengthening fuel economy standards in the USA for new vehicles in the early 2000s would have been technically and economically feasible, elected officials were not willing to spend the political capital needed to make this change (Geller et al., 2006). The calculation of policy ambition in TEMPEST is simple and does not account for some of the aspects of policy making that have been seen in the real-world messy processes of government. There is no variation in the relationship between PolCap spend and policy ambition, or in the types of policies assigned to different measures. There is no representation of policy design being influenced by the prioritisation of certain industries, regions or stakeholders by decision makers, due to political ideology (e.g. left- or right-leaning on the political spectrum) and the personal affiliations of decision makers.

2.2.3 Policy soup

The concept of "policy soup" is defined as a mixture of policy solutions developed by a sector's policy community, including legislators, bureaucrats, NGOs, and business leaders (Carter and Jacobs, 2014). Policy soup in TEMPEST is a stock that represents the total mix of currently active policy measures, and it is unique for each mitigation measure. The constituency of the policy soup stock changes over time, as new policy ambition is added and existing policies end. The length of time policies stay in the policy soup is determined by the average lifetime of policy measures. Thus, even if no new policy ambition is added in a model year, policy measures may still be available to drive mitigation if previously added policy measures are still running.

2.2.4 Public willingness to participate (PWP)

The concept of public willingness to participate (PWP) is used to indicate the likelihood that the expected outcomes of policies will be achieved. PWP is defined as a combination of social capital and an imperative to act. Social capital is the power, or agency, of actors in society to take action (Lin, 2011). Policies such as public information campaigns, network grants, and social marketing can improve social capital (Foxon et al., 2013). While social capital is essential, an imperative to act is also needed. The imperative to act can arise through extrinsic influences from mandates and rewards and punishments from policies; an intrinsic sense of responsibility; or other influencing factors such as changes to the economy. A deficit in the imperative to act is common, as illustrated in the terms “attitude-behaviour gap” (Peattie, 2010) and “intention-behaviour gap” (Caruana et al., 2016), both derived from real world studies. In other words, what people/organisations say and what they do with regards to emission savings are often different, and the tendency is for less action than expected, rather than more. PWP is also influenced by the user impacts associated with measures – the more disruption from a measure, the lower the PWP. PWP plays an important role in TEMPEST within the mitigation measure diffusion process, increasing or dampening the effect of policies to reflect the variability in policy achievements.

2.2.5 Policy-society feedbacks

Feedbacks between policy measures and societal responses have been identified by several authors, including the following. Feedbacks between policies and political pressures incorporate a complex, ever-changing, and interdependent mix of interest groups, large technical systems, market dynamics, user preferences, and radical niche-innovations (Roberts et al., 2018); feedback mechanisms between policy mixes and socio-technical systems can strengthen or weaken societal support for policies (Edmondson et al., 2019). Within these feedbacks there is a risk to the party of government, in a democracy, of unpopular policies leading to a loss of votes and the PolCap that they hold – termed “pushback” – and that pushback limits the ability of government to enact ambitious policies. For example, the UK’s “road lobby” resisted government ambitions to radically transform transport policy, with government ministers backing away from difficult decisions for fear of losing votes (Docherty and Shaw, 2011); the government of Northern Ireland fell partly due to a scandal from a badly run renewable heat incentive scheme (Muinzer, 2017); the car industry has lobbied against ambitious EU vehicle emissions reduction targets, with some manufacturers running emissions tests in a dishonest way, damaging public trust[ii]. Pushback can take the form of direct protests such as fuel strikes, which are politically damaging. In SD terminology, pushback is a kind of information feedback signal for government on public acceptance of governance.

TEMPEST represents policy pushback in a simple way. The amount of pushback depends on a combination of how strong the policy push is and how difficult it is for actors to comply with policies – influenced by how difficult and disruptive the measure is to develop or implement. In other words, the likelihood of pushback rises with more disruption or change being required of societal actors and there being simultaneously more pressure to act

2.3 Mitigation measure diffusion

TEMPEST models the whole process of mitigation measure development and diffusion.

2.3.1 Basis of diffusion simulation

Four established theories are used.

1. The **Bass diffusion model** (Bass, 1969), which is an augmented logistic model of innovation diffusion that includes the exogenous stimulation of early adoption (Sterman, 2000) – commonly known as an “S-curve”. TEMPEST adapts the SD model of Bass diffusion presented in (Sterman, 2000, p332), in which the adoption rate, which turns potential adopters into adopters, is driven by:

(i) a positive feedback loop, with adoptions resulting from word of mouth increasing the number of adopters, which leads to more adoptions from word of mouth, and (ii) external influences such as "advertising effectiveness". In the TEMPEST version the limits of adoption are not in terms of potential adopters, but in terms of a limit to the total potential for energy and emissions reductions for each mitigation measure; and "advertising effectiveness" is replaced by the influence of policy measures on diffusion.

2. The concept of **learning by doing** (LBD), simply defined as: *'the more something is made, the better it can be made*' (Sharpe and Lenton, 2021). In the economics of innovation LBD describes how technology learning and resultant cost reductions are related to cumulative investments in that technology (Anandarajah et al., 2013).
3. LBD can eventually lead to measure diffusion becoming **self-sustaining** without policy measure support. This is also termed self-generating or self-accelerating (Sharpe and Lenton, 2021). For example, in (Struben and Sterman, 2008) a simulation model of the adoption of alternative fuelled vehicles identified a tipping point after which government programmes could be withdrawn but the diffusion would continue.
4. The concept of **measure development indexes**. The process of technology development is described as having seven stages: idea/concept, basic research, applied research, development and design, engineering and manufacturing, marketing, and product/service (Balachandra et al., 2010). There are several indexes for measuring technology development which can be applied to different types of mitigation measures, such as: "technology readiness levels" (Mankins, 2009); the "carbon capture and storage readiness index" (Consoli et al., 2017), and the "commercial readiness index" (Animah and Shafiee, 2018).

2.3.2 Measure typology

A measure typology simplifies the simulation of mitigation measure diffusion in TEMPEST. It was developed through observation of UK historical patterns of measure diffusion 1980 to 2019, identifying the basic characteristics of different measures and how they influence the diffusion process, including interactions with wider political and social factors. The basic characteristics are: novelty and difficulty, user impacts, international RD&D, commercialisation tipping point, and self-sufficient tipping point. There are 9 measure types in the typology, and 39 mitigation measures. Some of the measures are a group of measures more usually modelled separately, such as residential energy efficiency. The 39 measures are assigned a type in the typology. Details of the typology are provide in the supplementary information.

2.3.3 Phases in measure diffusion

Table 1 presents details of the three phases of measure diffusion in TEMPEST. The speed at which measures move through the phases is unique for each measure and dependent on policy ambition. Some measures start in phase two or three at the start of simulation because they were already mature at that time, such as building energy efficiency.

	Phase One (development)	Phase Two (implementation with policy measures)	Phase Three (self-sufficient implementation)
When active	From measure conceptualisation to commercialisation	From measure commercialisation to self-sufficiency	From self-sufficiency to the end of the diffusion process
Function	Creates feasible potential from theoretical potential.	Turns the feasible potential created in phase one into measure implementation that provides energy and emissions savings.	Continues the conversion of feasible potential into energy and emissions savings started in phase two, but without policy support.
Mechan-isms	LBD that achieves measure commercialisation is modelled as follows: niche innovation (partly driven by policy measures) attracts investment in research, design and development (RD&D), which leads to technology learning, which improves niche innovation, etc.	Measure implementation is driven by a combination of PWP, feasible potential, how much of the potential has already been implemented, and the maximum measure implementable per year. Increases in measure adoption increase LBD, which improves measures and leads to more adoption.	Measure implementation is the same as in phase two but without policy ambition increasing PWP. Measure implementation continues until: (i) there is no more feasible potential, or (ii) sector energy or emissions are at their minimum, or (iii) the national mitigation target has been reached.
Policy measures	Investment in early stage lab-based RD&D, funding for technology demonstration projects, and funding for pilot studies.	Incentive schemes like feed in tariffs, equipment regulation, power sector market mechanisms such as the Contracts for Difference scheme[iii], guaranteed prices (strike price) for new power capacity, carbon taxes, and consumer information schemes.	
Differences for behaviour-al measures	Behavioural measures do not go through this phase.	**Behavioural measures:** do not achieve LBD; disposable income decreases PWP; measures produce negative energy savings if PWP is < 0. **Technological measures:** achieve LBD; disposable income increases PWP for mass-market technological measures; measures are not implemented when PWP < 0; only produce negative energy savings for fuel switching measures.	Similar to phase two, except behavioural measures continue to get policy support if needed.

Table 1: Details of the three phases in mitigation measure diffusion

3 Model development

This section briefly describes the building and calibration of TEMPEST. Further details are provided in the supplementary information.

3.1 High-level view of model feedbacks

A simple representation of the main feedback loops in TEMPEST is shown in Figure 1, as a causal loop diagram. This portrays the high-level structure of the model.

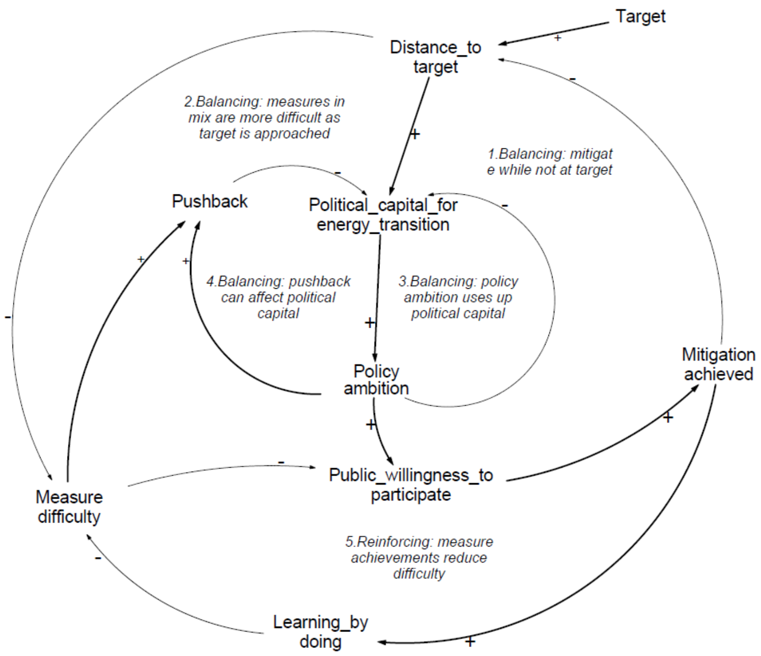

Figure 1: Simple representation of the feedbacks in TEMPEST as a causal loop diagram

The feedback loops are explained as follows.

Loop 1. Balancing: mitigate while not at target. Loop 1 drives the whole model, seeking to achieve mitigation while the distance to target is non-zero. The model stops running once the target is reached or the year reaches 2080. The target has changed since 1980, as government responded to increasing confidence in climate science and new international agreements were made. In 2019, the UK target was set to be net zero emissions by 2050 and so the target does not vary in the future period. Relation to model conceptualisation: purpose of the model (section 2.1) and basic SD modelling theory (section 2.1.2) of modelling a goal-seeking system as a balancing loop.

Loop 2. Balancing: measures in mix are more difficult as target is approached. Loop 2 reflects changes in the overall mix of mitigation measures with potential for development (theoretical) and/or implementation (feasible). Since 1980, much of the "low hanging fruit" of mitigation measures has been used, and much of the mitigation potential for the future is provided by measures that are increasingly more technologically difficult (e.g. typology type 9) and/or more impactful to users. Thus, the changing mix of mitigation measures that are available for policy ambition in TEMPEST reflects this trend. Relation to model conceptualisation: use of theoretical and feasible potential for measures in phases one to three of diffusion (section 2.3.3), measure typology (section 2.3.2) and the relative difficulty of measures due to their characteristics.

Loop 3 Balancing: policy ambition uses up political capital. In loop 3, PolCap is used to create policy ambition. The availability of PolCap limits the amount of policy ambition that can be set by government and therefore the rate of mitigation measure diffusion. The limitation on policy ambition does not necessarily mean that mitigation will not happen, however, since in some cases loop 5 will continue without a strong policy push – such as when measures are in phase 3. Relation to model conceptualisation: definition of PolCap (section 2.2.1) and policy ambition (section 2.2.2).

Loop 4 Balancing: pushback can affect political capital. Loop 4 reflects the relationship between policy ambition and societal responses, allowing the concept of pushback to be modelled. Pushback is more likely with simultaneous increases in measure difficulty (behavioural or technological) and policy ambition. As pushback increases, PolCap decreases. Relation to model conceptualisation: definition of pushback (section 2.2.5).

3.1.1 Loop 5 Reinforcing: measure achievements reduce difficulty

Loop 5 is the key reinforcing loop through which energy and emissions savings are achieved, representing LBD in all phases of diffusion. Loop 5 reduces measure difficulty, which increases PWP and therefore reduces the need for policy ambition. Growth in loop 5 also reduces pushback, avoiding loss of PolCap. Loop 5 can be slow to take off for some measures if there is insufficient policy ambition at the right time. Relation to model conceptualisation: LBD theory (section 2.3.1).

Several loop combinations involving loop 5 may become important on the route to net zero. The combination of loops 4 and 5 forms a reinforcing loop that can run in two directions. If loop 5 reduces average measure difficulty fast enough then “negative pushback” would increase PolCap and further increase the rate of adoption of measures. A weak loop 5 makes pushback more likely, as high measure difficulty will combine with the high policy ambition needed to meet the target. Loop 5’s growth rate might be limited by unavailability of sufficient policy ambition through loop 3, due to barriers that reduce PolCap such as economic downturns. Loop 2 can be counterbalanced by loop 5. If loop 5 reduces mitigation measure difficulty faster than the rate at which more difficult measures are required over time, then loop 2 will become insignificant which will speed up the transition.

3.2 SD diagram

Figure 2 illustrates the stock and flow structure of TEMPEST as a simplified version of the full SD model, and an expanded version of Figure 1. The following are notable in the model.

- The flow of mitigation through stocks on the right of the diagram is from theoretical potential, to feasible potential, to achieved mitigation, in line with the diffusion process discussed in section 2.3.3.
- Loop 5 from Figure 1 is split into two: one for LBD in mitigation measure development (R1) and one for LBD in measure implementation (R2).
- The stock of PolCap, on the left, is increased at a rate relative to the distance to the target and is decreased when it is used to create policy ambition. It is also influenced by drivers and barriers and pushback.
- Policy ambition is assigned through a policy choice engine, which is a simple representation of the process of policy making that goes on in government. Policy ambition is assigned to measures based on how much PolCap is available, the cost of the measure (based on the measure type), and available theoretical (phase one) or feasible (phase two) potential of measures.

The development of TEMPEST included several stages – initial build, calibration to historical data, and model validity testing. Details of the calibration process are provided in the supplementary information.

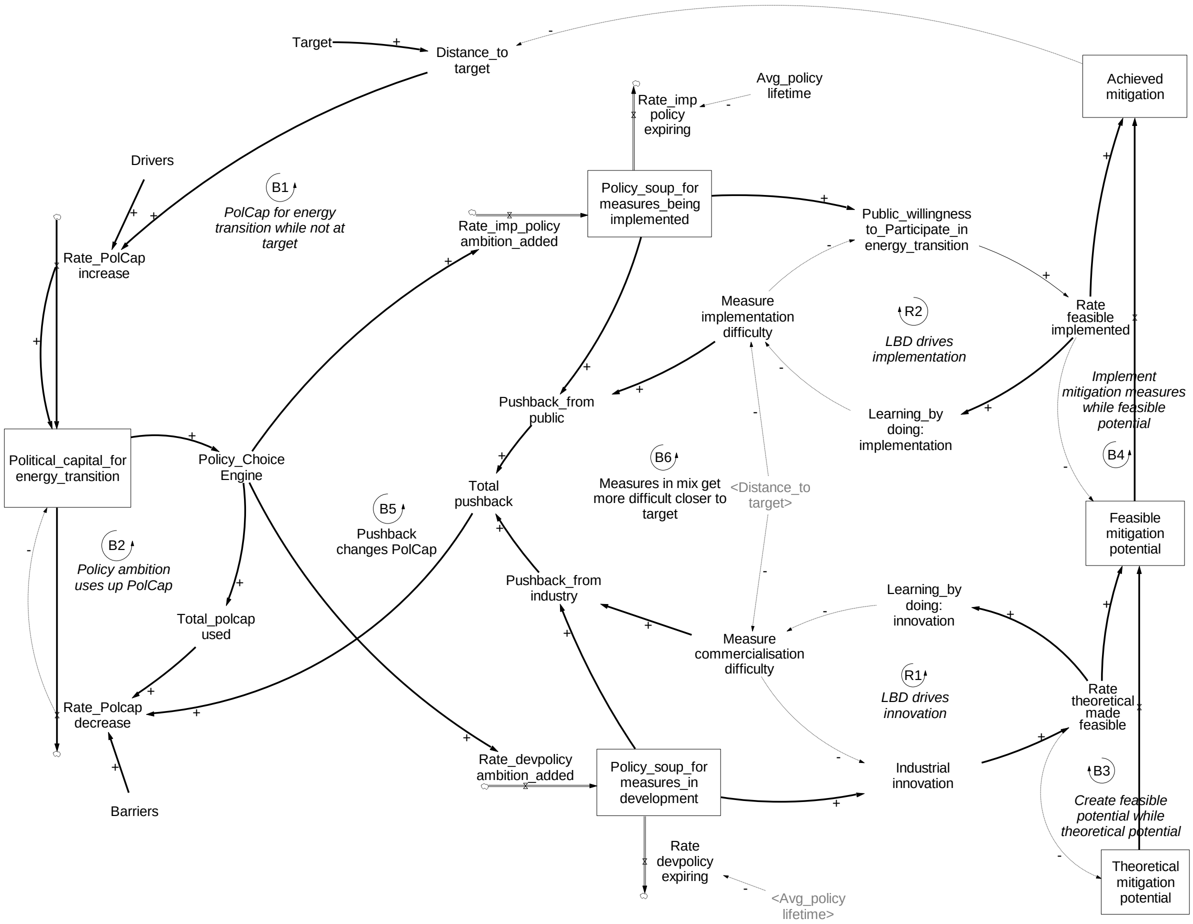

Figure 2: System dynamics diagram of TEMPEST[iv], simplified from the full model.

4 Model results – the future of UK energy transition

4.1 Uncertainty analysis

An uncertainty analysis explores the range of uncertainty in two key indicators:

1. The year of reaching net zero, for which the target is 2050
2. Cumulative emissions between 2020 and the year of reaching net zero or 2080 (whichever comes first), for which the target is to limit emissions to within the budget of 5626 MtCO_2 (based on the Committee on Climate Change's CO_2 projections from 2020 to 2050 (CCC, 2021)).

A sensitivity test (using the Monte Carlo simulation feature in Vensim) simultaneously varies seven sensitivity variables across 1000 cases. Details are provided in the supplementary information.

4.1.1 Key indicators

Figure 3 (left) shows a histogram of future cumulative emissions. The distribution is positively skewed despite sensitivity variables being varied normally around a neutral mean. This is partly because mitigation achievements are limited by the starting values for energy and emissions, but increases in emissions are not similarly limited. Figure (right) shows the year that cases reach the target (for those that do) against total emissions. Emissions increase as the year of reaching the target increases, although this trend levels off after 2060. The uncertainty spread in emissions increases up to 2060, and then decreases.

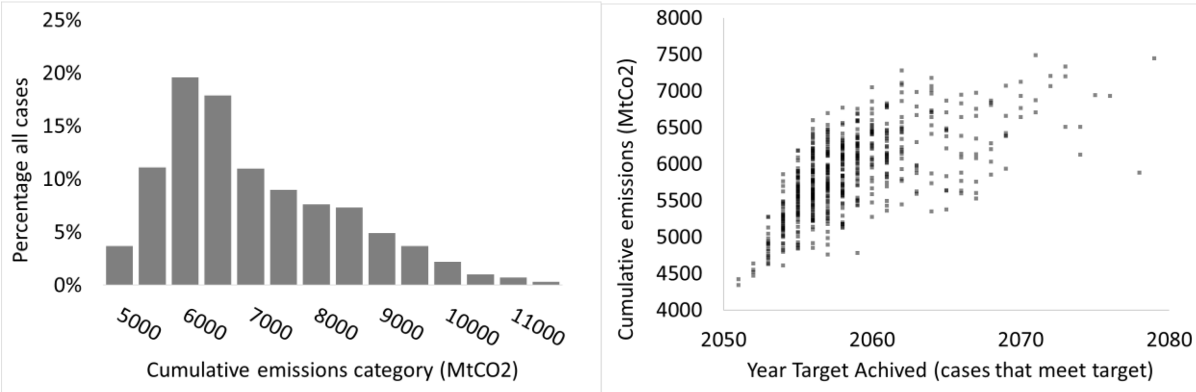

Figure 3: Probability density for cumulative emissions (left) and emissions by year target is met (right).

4.1.2 Policy ambition and achieved mitigation

Based on the model design, it would be expected that policy ambition and PWP are negatively correlated with emissions.

Figure 4 illustrates these relationships, showing a decrease in emissions associated with increases in policy soup (left) and PWP (right) (Note: policy soup and PWP values are the sum across all measures). The relationship is not linear, however; the best fit is a negative power equation.

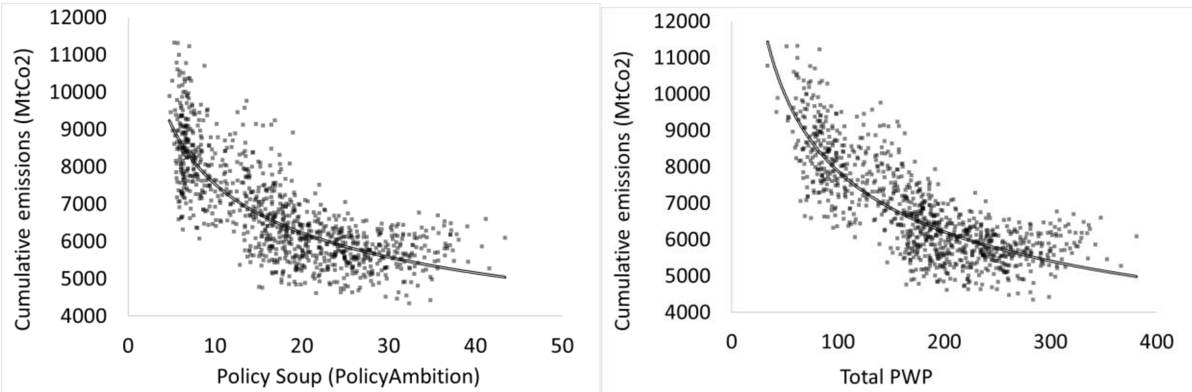

Figure 4: Relationships between total policy ambition and total emissions (left), and between total PWP and total emissions (right).

4.1.3 Behavioural changes and policy

Behavioural measures were seen to have played an important role in energy and emissions changes in the historical period. Figure 5 (left) maps savings from behavioural measures against policy ambition in the future period. A tipping point is seen – once the size of policy soup falls too low, behavioural measures produce medium to strong negative savings. Figure 5 (right) shows the relationship between behavioural measure savings and total emissions. Only with positive behavioural savings do emissions fall to a level comparable to the CCC carbon budget. In other words, in these model runs technology measures do not provide sufficient savings to counter energy consumption increases when energy service demand rises quickly.

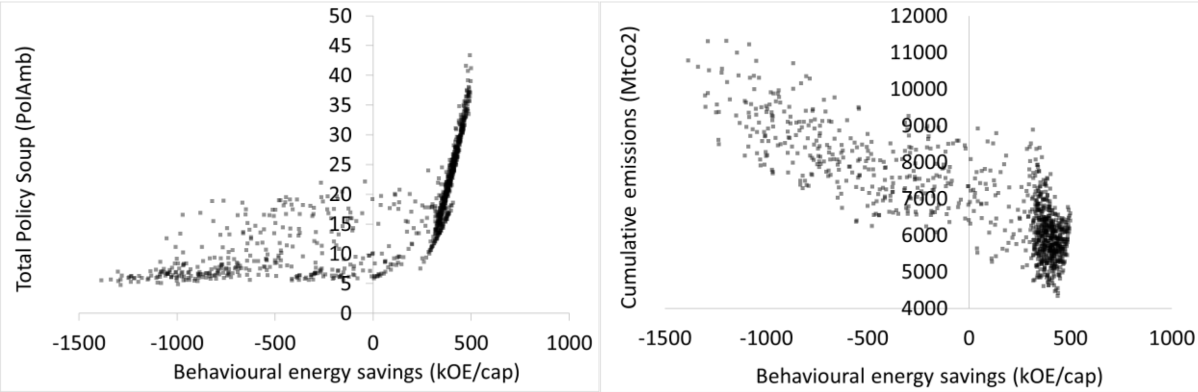

Figure 5: Relationships between policy ambition and energy savings from behavioural measures (left), and between emissions and behavioural measure savings (right).

4.1.4 Uncertainty groups and measure achievements

The 1000 sensitivity cases were grouped by outcome into five groups, with decreasing achievements in reducing cumulative emissions, from group 1 to 5, as follows: (i) Less than the CCC budget (20% of cases); (ii) Less than 7000 MtCO_2 (43% of cases); (iii) Less than 8000 MtCO_2 (17% of cases); (iv) Less than 10000 MtCO_2 (18% of cases); (v) More than 10000 MtCO_2 (2% of cases). While group 5 has very low probability, it provides an indication of what a worst case would look like. TEMPEST was run using the average sensitivity variable values for the five groups, so each group is represented by a single model run. Supplementary information provides details of sensitivity variables and indicators of model response across the 5 groups.

Figure 6 (left) shows average annual changes in energy use for demand sectors. Groups 3, 4 and 5 show negative savings from behavioural measures. Additions of low-carbon power are much lower for groups 3 to 5. Energy savings from non-behavioural measures are lowest for group 3, which has the lowest disposable income of all the groups – likely due to income influencing ability to purchase new low carbon measures.

Figure 6 (right) shows reductions in energy use and carbon intensity in the final year of the model run, as a percentage of 2019 values. Energy savings decline when going from groups 1 to 5. All groups show increases in electricity use, due in part to fuel switching but also due to increases in energy services that use electricity. Reductions in the carbon intensity of electricity occurs at a similar level across all groups, with power measures being less influenced by changes in PWP. Reductions in the carbon intensity of nonelectric fuels decreases from group 1 to group 5, since some of the more difficult measures, such as hydrogen (H2) fuel and carbon capture and storage (CCS), require more policy ambition which may not be available.

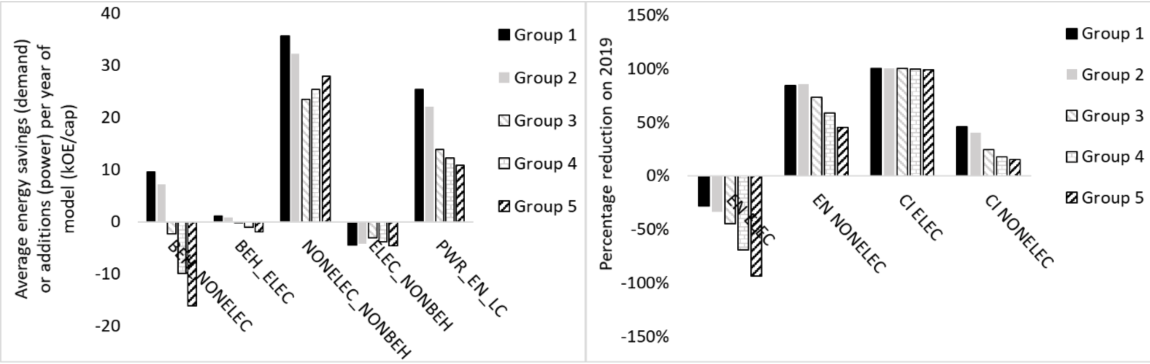

Figure 6: Energy and emissions achievements by groups of uncertainty analysis cases. DMST = domestic (residential); NDMS = non-domestic sectors; TRNA = air transport; TRNS = surface transport; BEH= behavioural; CI = carbon intensity; BEH_NONELEC and BEH_ELEC are energy demand savings from behavioural measures for nonelectric and electric fuels; NONELEC_NONBEH and ELEC_NONBEH are energy demand savings from non-behavioural measures; PWR_EN_LC is addition of low-carbon electricity generation in the power sector.

4.1.5 Behaviour of uncertainty groups over time

Figure 7 presents four key indicators over time, in the future period, for the five groups. At top left is shown annual emissions. Groups start to diverge after 2030, with groups 1 to 3 reaching net zero between 2056 and 2068, while groups 4 and 5 failing to meet the target before 2080 and showing rising emissions after 2040. At top right is shown total PWP. Groups 1 and 2 have high PWP between 2030 and 2050, but groups 3 to 5 show declining PWP after 2030, which slows down the diffusion of measures and fails to dampen energy services demand. At lower left is shown PolCap over time, with trends for each group illustrating the mixture of political shocks, drivers and barriers, and feedbacks that increase or decrease PolCap. Group 1 has low barriers, high drivers, no change to disposable income, lower population than forecast, and a positive shock, all of which increase PolCap. In contrast, group 5 has high barriers, low drivers, much higher disposable income, higher population than forecast, and a negative shock. Thus, enough PolCap is available for groups 1 and 2 but not for groups 3 to 5. At lower right is shown the share of required mitigation in each model year as feasible potential, across all measures. This illustrates where a lack of niche innovation can slow down mitigation. Groups 1 to 3 all achieve enough feasible potential eventually, but groups 4 and 5 fail to generate enough.

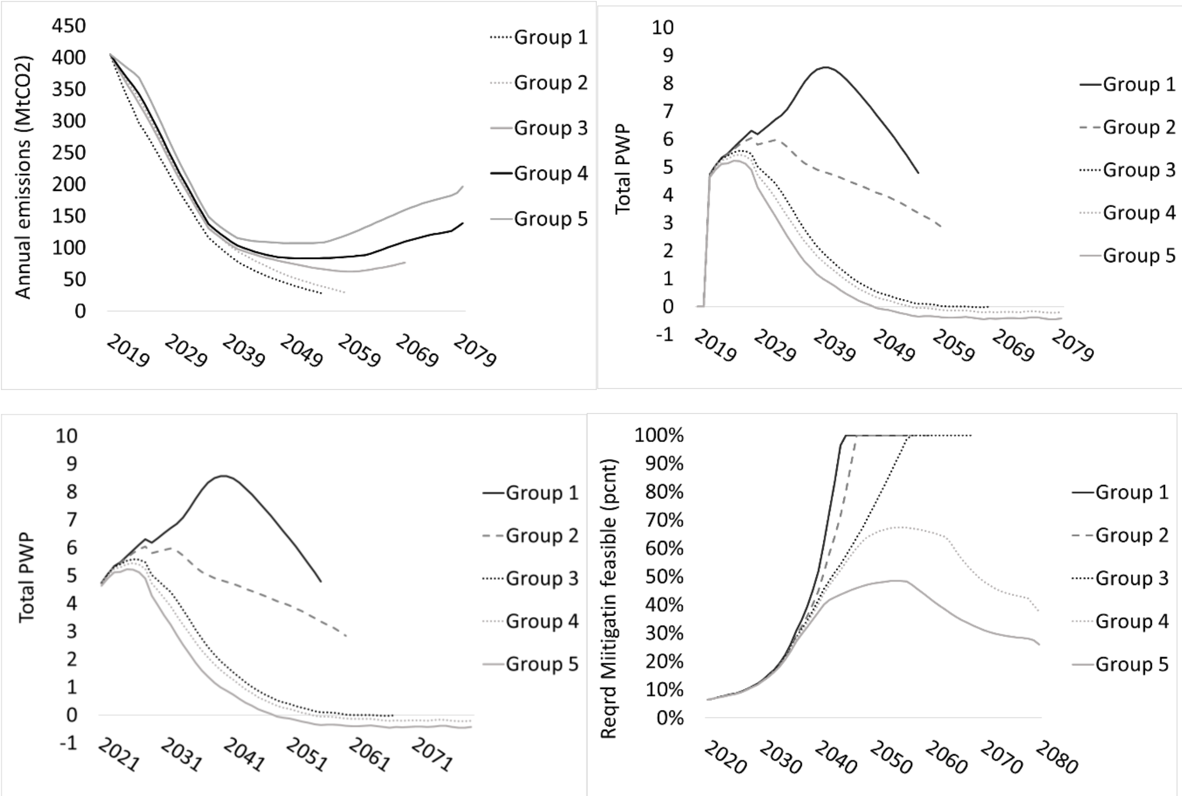

Figure 7: Behaviour over time for key model indicators, by uncertainty groups – annual emissions, total PWP across measures, PolCap, and share of required mitigation that is feasible. Values are shown until the year of reaching net zero or 2080 (whichever is first).

5 Discussion

This section reflects on several aspects of the model and its outputs.

5.1 Nonlinearity and endogenous uncertainties

The uncertainty analysis in section illustrates wide variability in the socio-political feasibility of achieving energy transition targets in the UK. The question remains as to whether this variability is caused by non-linear or linear system dynamics. The core part of TEMPEST, measure diffusion that responds to the requirement to meeting mitigation targets, is basically a nonlinear first-order system – the S-shaped growth curve. First order systems do not oscillate (Sterman, 2000, pp 290), and TEMPEST did not produce any surprising dynamical responses during uncertainty testing. In theory, the system could exhibit second order behaviours in future, however, based on the potential for unexpected interactions between loops 2 and 4 in Figure 1. If those in governance fail to estimate the strength of increase in measure difficulty up to net zero, then emissions reductions will be too slow. There could then be a strong policy push, but combined with the higher difficulty of the targeted measures this would cause a large pushback effect. There would likely be recovery over time after the drop in PolCap, although perhaps too slow to ramp up measure implementation at the rate required.

During the calibration of TEMPEST pushback was set to have a limited influence on system behaviour, since there is not enough evidence from the historical review that it can have a dominant effect on the whole transition – although it has certainly contributed to failures of certain policies. To test potential for second order behaviours, TEMPEST was run with an increase in two key uncertainties in its endogenous responses: the strength of pushback, and the difficulty of diffusion of measures with the type called “branching”. The branching type includes the most difficult and novel technologies that are expected to provide savings in future but are not yet commercialised and at cost parity, as of 2021. They include CCS and H2 in the power sector and non-domestic sectors to reduce carbon intensity of fuels, and fuel switching to electricity or H2 in air transport. These technologies, apart from their high cost and technological complexity, lack co-benefits in addition to emissions savings making investment more politically expensive and diffusion more uncertain overall.

Three TEMPEST runs explore the influence of these two uncertainties. All have default values for the exogenous variables varied in the uncertainty analysis, including drivers and barriers for PolCap; there are no political shocks. In other words, differences between cases are due to endogenous responses. The 1st case has no changes in pushback; the 2nd case has high pushback; the 3rd case has high pushback and increased difficulty for branching measures. Cumulative emissions increase by 11% and 28% in the 2nd and 3rd cases compared to the first case, respectively. The 2nd case shows a delay of 10 years in reaching the target, and the 3rd case does not reach the target before 2080. Figure 8 (left) shows annual emissions for the three cases. The increasing strength of pushback and reduced learning by doing is seen in a slowing down of emissions reductions for cases 2 and 3 after 2040. Figure 8 (right) shows total PolCap each year, with increasing dampening of system responses to the need for mitigation seen as large decreases in PolCap after 2030 and slow recovery of PolCap levels – taking 10 years to start recovering in case 2, and 25 years to start recovering in case 3. Negative PolCap for case 3 leads to a lack of mitigation progress after 2050.

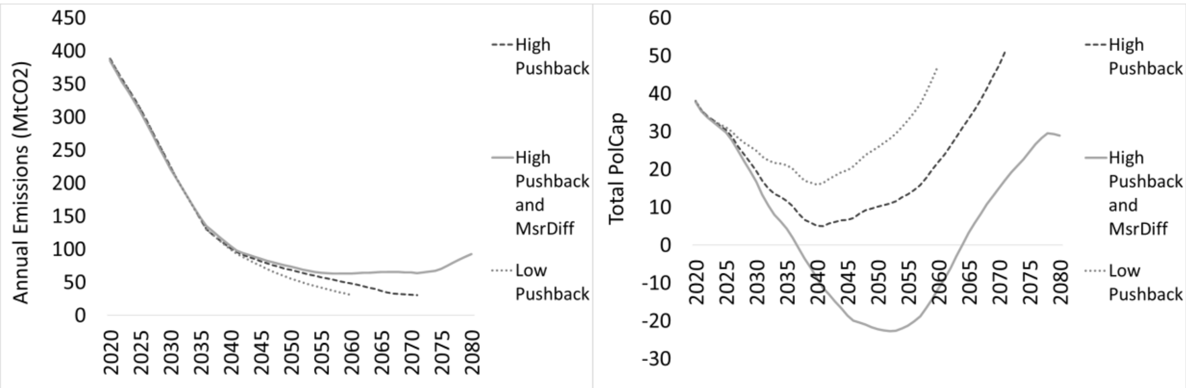

Figure 8: Annual emissions for cases with low pushback, high pushback, and high pushback with increased difficulty of branching measures (left), and changes in PolCap over time in the three cases (left).

5.2 Supporting policy making

To some readers, the model may seem to sit uncomfortably in a balance between being highly conceptual, and being a practical tool for supporting decision making that can be compared to existing trusted models. One argument for accepting the model as a source of new insights to inform energy transition governance, or at least add to the body of STET work, is that the model design is based on a wide-ranging review of the literature combined with historical data. The key concepts presented in section 2 are derived from political science, the social sciences, energy and emissions mitigation work.

Combining these concepts with a review of experience from 40 years of energy policy and programmes in the UK enabled a whole energy system dynamic hypothesis to be developed that is grounded in real-world experience. This was further emphasised once the dynamic hypothesis was translated into a model and the model was calibrated to historical data for energy, emissions, policies, and mitigation measures. The resulting model structure presented in Figure 1 illustrates the revised dynamic hypothesis as a system of feedback loops.

More work needs to be done to further validate and build confidence in the model. One way would be to incorporate qualitative case data on different aspects of energy transition in the model, bringing in a different mental models about the problem space from a variety of actors (Schaffernicht and Groesser, 2011). Another way would be to incorporate new evidence to review some of the simplifying assumptions about variable relationships used in TEMPEST. New reports are being published at a fast rate as the push to achieve net zero gets stronger across the world. For example, the citizens assembly that was run in the UK provides new findings about public willingness to change energy behaviours (House of Commons, 2020). TEMPEST is a new model and its usefulness for governance has yet to be proven. However, early conversations with civil servants in the UK government indicate a strong interest in it as fulfilling a research need thy have known about for some time – namely being able to relate social and political feasibility with technological and economic feasibility together in one place.

5.3 Contributions

TEMPEST has contributed the following insights to the field of STET modelling.

1. A conceptual view of the socio-political-technological feedbacks involved in the process of energy transition, and the particular roles of political and societal factors in those feedbacks. Evidence on the importance of managing feedbacks to limit uncertainty in energy transition outcomes. The importance of including at least some representation of political and societal factors when modelling energy transition.
2. A simplified way of modelling mitigation measure diffusion that combines the basic characteristics of mitigation measures, defined in a measure typology, with varying responses of actors involved in implementing measures, and varying levels of policy support during three phases of diffusion. This approach includes less economic and technological data, compared to the standard method of modelling measure diffusion, but adds data on political and social issues.
3. An estimate of the range of socio-political uncertainty in meeting the net zero target. While the majority of cases reach net zero before 2080, low probability but high impact outcomes show a doubling of cumulative emissions from 2020 to 2080, compared to the best case. This indicates that the socio-political feasibility of reaching the net zero target in time is likely less than the techno-economic feasibility that has been estimated through standard energy systems models.
4. Identification of risks in energy transition from unhelpful directions in feedbacks between societal actors and government. Model testing shows that an increase in societal pushback to unpopular policies could delay meeting the target by ten years, and when combined with more difficult than expected implementation of key measures the target would be missed. Policy making may need to be more responsive and agile in future should these system responses arise.

5. Identification of the importance of having enough PolCap early on in the period 2021 to 2050. There is an inverse correlation between the amount of PolCap available between 2020 and 2030 and the total amount of mitigation needed before reaching net zero. While spending a lot of PolCap early on could be risky for politicians, the rewards for society would be seen in shortening the length of the energy transition and reducing its overall disruption. This observation illustrates a common pattern seen in other system dynamics studies, named “worse before better”. When changes are made to a system to improve it, increased costs and/or reduced useful outputs are often seen, although only temporarily. If managers abandon the improvement efforts too early, the end result will be overall dis-benefits (Lyneis and Sterman, 2016). Similarly, the short term pain of high spending of PolCap early on would greatly improve the whole energy transition process, but only if efforts are not abandoned early due to political difficulties. PolCap is influenced by many factors not related to energy, however, so there is no guarantee that enough will be available when needed. Making use of societal-level drivers of energy transition could in theory fill gaps that may exist at the governance level, working in tandem with top-down policy making. Finally, achieving early energy transition would place the UK in a position of leadership in the world on energy transition, increasing PolCap and creating new co-benefits such as increased exports of expertise and technologies.

5.4 Further work

Plans for further development of TEMPEST include: (i) Adding more detail in the policy choice engine, so that mitigation measures receive several different types of policy measures, allowing optimisation of policy strategy to make the best use of available PolCap. This could include adding detail on the trade-offs policy makers face in prioritising policy measures, between technological diversity and technology scale-up (van den Bergh, 2008). (ii) Adding economic data for measures and fuels, and widening the detail in the categories of measures, which would bring TEMPEST closer to mainstream energy system models and enable findings to be more easily compared. (iii) Adding representation of societal-led innovations, such as smart technologies linked to social media, which could contribute to measure implementation and increases PWP. (iv) Improving the simplified assumptions in the calculations used to represent societal pushback, by using evidence gained through working with government policy makers and analysts. (v) Including energy price factors in modelling of energy service demand represented by behavioural measures. Should rapid decarbonisation push up retail energy prices significantly, there would be changes to service demand through energy price elasticity and direct rebound effects from efficiency (Stapleton et al., 2016).

6 Conclusions

The conceptualisation, design, build, and initial findings from a new model of energy transition have been presented. The model, TEMPEST, was designed to contribute to a research gap in energy transition modelling: enabling social and political factors known to be important to energy transition in the real world to influence the quantitative models used to support decision making.

TEMPEST is a system dynamics simulation model that represents the UK energy system, its emissions and fuels, and the key mitigation measures that have been used, or are planned to be used, for achieving a net zero emissions target. The model was calibrated to approximately reproduce the energy system behaviour between 1980 and 2019, and then the future was simulated from 2020 to 2080. An uncertainty analysis, based on variations in exogenous variables, revealed that a majority of the cases would meet the net zero target before 2080, but only 20% would stay within the required carbon budget up to 2050. Analysis of five groups of uncertainty cases showed strong differences in energy savings from behavioural measures and the worst group had cumulative emissions twice as high as the best group. Lowest emissions occurred when there was a positive shock that temporarily increased political capital, the expected trajectory for disposable income, low barriers and high drivers to energy transition, and lower than expected population growth. Testing uncertainty in system responses, including high public pushback to policies and higher than expected difficulty in new technologies, revealed that reaching net zero could be delayed by a decade or more due to losses in political capital and slower implementation of mitigation measures.

Key contributions from the study include: A conceptual view of the socio-political-technological feedbacks involved in the process of energy transition, and evidence on the importance of managing the feedbacks to limit uncertainty in transition outcomes. A simplified way of modelling mitigation measure diffusion that combines the basic characteristics of mitigation measures, defined in a measure typology, with varying responses of actors involved in implementing measures, and varying levels of policy support during three phases of diffusion. An estimate of the range of socio-political uncertainty in meeting the net zero target. The socio-political feasibility of reaching the net zero target in time is likely less than the techno-economic feasibility that has been estimated through standard energy systems models. Identification of risks in energy transition from unhelpful directions in feedbacks between societal actors and government. An increase in societal pushback to unpopular policies could delay meeting the target by ten years, and when combined with more difficult than expected implementation of key measures the target would be missed. Identification of the importance of having enough political capital early on in the period 2021 to 2050, since there is an inverse correlation between political capital availability between 2020 and 2030 and the total amount of mitigation needed before reaching net zero. While spending a lot of political capital early on could be risky for politicians, the rewards for society would be seen in shortening the length of the energy transition and reducing its overall disruption. Since political capital is influenced by many factors not related to energy, societal-level drivers of energy transition may be needed to work in tandem with policy measures. Achieving early energy transition would place the UK in a position of leadership in the world on energy transition, increasing political capital and creating new co-benefits such as increased exports of expertise and technologies.

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[iii] The Contracts for Difference scheme is the government's main mechanism for supporting low-carbon electricity generation. www.gov.uk/government/publications/contracts-for-difference/contract-for-difference

[iv] To interpret the model: Positive causation is represented by solid arrows with a plus ("+") sign. Negative causation is represented by dashed arrows with a minus ("–") sign. Reinforcing feedback loops are named R1, R2, etc., and grow indefinitely until interrupted. Balancing feedback loops are named B1, B2, etc., and are goal seeking, growing until a goal or limit is reached.