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LETTER

Socio-technical modelling of UK energy transition under three global SSPs, with implications for IAM scenarios

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Abstract

The potential for using findings from socio-technical energy transition (STET) models in integrated assessment models (IAMs) has been proposed by several authors. A STET simulation model called TEMPEST, which includes the influence of societal and political factors in the UK's energy transition, is used to model three of the global shared socioeconomic pathways (SSPs) at the national level. The SSP narratives are interpreted as inputs to TEMPEST, which drive scenario simulations to reflect varying societal preferences for mitigation measures, the level of political support for energy transition, and future economic and population trends. SSP1 and SSP2 come close to meeting UK net zero targets in 2050 but SSP5 does not reach net zero before 2080. An estimate of the total societal, political, and economic cost of scenarios indicates that while SSP1 achieves the best emissions reductions it also has the highest total cost, and SSP2 achieves the best ratio between rate of emissions reductions and total cost. Feasibility appears to be highest for SSP2 since it is the least different to historical precedent. Current UK government energy strategy is closer to the narrative in SSP5, however, which has the highest total cost and exceeds an estimated carbon budget by 32%. Three key TEMPEST findings are recommended for use in IAMs: (i) the uncertainty in emissions savings due to variability in political and societal support for energy transition, (ii) the influence of negative societal pushback to policies in achievement of expected policy outcomes, and (iii) the combined influence on energy service demand of disposable income, public willingness to participate, and user impacts from measures.

1. Introduction

Socio-technical transitions (STTs) theory (Geels *et al* 2020) is a middle-range theory, positioned between general, unified theories and minor working hypotheses that arise in day to day research (Merton 2007). STT theory argues that changes to the technological landscape include a weaving together of '*technical artefacts, organisations, institutional rule systems and structures, and cultural values*' (Sovacool *et al* 2018). Socio-technical energy transition (STET) models incorporate STT theory into quantitative modelling of energy transition to net zero emissions, capturing '*the co-evolutionary nature of policy, technology and behaviour*' (Li *et al* 2015). Because STET models are informed by a growing body of case studies, they provide important insights about the real-world complexities of energy transition (Holtz *et al* 2015). Examples of STET models include: the importance of social acceptance in the realistic achievement of a cost-optimal generation portfolio (Cotterman *et al* 2021), effects of socio-technical factors on electricity grid flexibility (Sheykhha and Madlener 2022), the role of energy industry actors in power decarbonisation (Barazza and Strachan 2020), the importance of timing and strength of leadership from government in energy transition (Li and Strachan 2017), interactions between social learning and technological learning (Edelenbosch *et al* 2018), and the evolutionary nature of the process of product innovation and diffusion (Mercure 2018).

Global integrated assessment models (IAMs) are heavily relied upon by those planning global and national responses to climate change, and they feed into IPCC reports (IPCC 2022). Important metrics provided by IAMs related to energy transition include the strength of policy measures needed and mixes of emissions mitigation measures. Since all models are, by definition, simplified representations of reality, it is important to understand what effects the simplifications within IAMs may have on the real-world feasibility of the modelled decarbonisation pathways they produce. While the techno-economic feasibility of decarbonisation scenarios can be evaluated, questions remain about the risk of political backlash from those negatively affected (Rodrigues *et al* 2022) and the political feasibility of the more challenging solutions included in mitigation pathways (Jewell and Cherp 2020). Incorporating findings from STET models into IAMs has several potential benefits including '*improved realism of models, more effective and realistic solutions at various time horizons*' (Trutnevyte *et al* 2019).

This study advances the proposition for incorporating findings from STET models into IAMs, in the context of the UK's energy transition to net zero. The UK provides an example of an industrialised nation that should, in theory, be well placed to achieve its climate target, with its legal commitment to decarbonisation (Climate Change Act of 2008), domestic high-tech sectors, and mature economy. A STET simulation model of UK energy transition, called TEMPEST (Freeman 2021), is used to explore issues in the real-world feasibility of modelled decarbonisation pathways. The study achieved the following: (a) modelling, in a national STET model, of three of the five global shared socioeconomic pathways (SSPs) (Riahi *et al* 2017); (b) an estimate of the total societal, political and economic cost of each scenario related to its achievement of emissions reductions; (c) a discussion of the likely feasibility of scenarios occurring and of the UK achieving its energy transition targets; and (d) a comparison of results from modelling the same scenarios in TEMPEST and an IAM (IMAGE) with recommendations for ways in which TEMPEST modelling results could improve understanding of the feasibility of IAM modelled pathways.

2. Methodology

2.1. SSP narratives

SSPs are well defined in the literature (Riahi *et al* 2017, Fricko *et al* 2017, Rogelj *et al* 2018b) and in particular for application to the energy system in (Bauer *et al* 2017). SSPs were used in this study to allow for a linking of STET and IAM models, since published IAM datasets are based on one of the SSPs. Three SSPs were chosen—SSP1, SSP2, and SSP5—which provide a range of energy transition narratives. The parts of the narratives that are relevant for energy transition are summarised in table 1.

2.2. The TEMPEST model—key concepts

TEMPEST simulates UK historical trends in energy and emissions from 1980 to 2019, and from 2020 onwards it can be used to explore pathways towards the UK's net zero target by 2050. The theory, structure, calibration and uncertainty testing of TEMPEST is explained in detail in (Freeman 2021) and its supplementary information (SI). Uncertainty testing using TEMPEST (detailed in Freeman 2021) found a risk of doubling of cumulative emissions in low probability but high impact cases, and significant risks from unhelpful feedbacks between societal actors and government if they increase relative to the past. Few similar models to TEMPEST exist; however, (Moore *et al* 2022) presents a stylised model of the climate–social system, which reveals that variations in global emissions pathways are influenced by public perceptions of climate change and the responsiveness of political institutions. Table 2 presents key concepts and variables in TEMPEST.

2.3. TEMPEST scenario inputs

Data inputs (table 3) enable TEMPEST to simulate the three SSP narratives from table 1. The scenario inputs also indicate what changes might be seen in society and in public policy making if the scenarios were to occur. There are four types of inputs: (a) those affecting PolCap including future trends in PolCap drivers and barriers and a positive 'shock' of a temporary surge in PolCap (e.g. due to increased societal support for decarbonisation or an event such as the COVID-19 pandemic that forced a (temporary) reduction in energy use (Kikstra *et al* 2021)); (b) disposable income; (c) population[1]; and (d) adjustments to how PolAmb is assigned to different types of mitigation measures. Details on these values are in the SI, section 4.

2.4. TEMPEST structure

Most of TEMPEST's simulation behaviours are endogenously generated from a system of interconnected feedback loops (shown in figure 1 as a causal loop diagram Sterman (2000)[2])—in line with the system dynamics modelling methodology (Forrester 1971). During simulation, PolCap is used to create PolAmb (i.e. policy measures). PolAmb drives either early development of mitigation measures up to commercialisation, or deployment of measures up to the point that they become self-sufficient and no longer need policy support (Struben and Sterman 2008). PolAmb increases the PWP for different measures, which enables deployment of mitigation measures

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[1] Population and economic trends introduced to TEMPEST for scenarios were derived from data used in IAMs for the same scenarios (SSP Database https://tntcat.iiasa.acat/SspDb/dsd?Action=htmlpage&page=about) and data for the UK from the Office of National Statistics (www.ons.gov.uk/).

[2] A more detailed system dynamics diagram of TEMPEST, showing stocks and flows, is provided in (Freeman 2021), figure 2.

Table 1. Characteristics of three SSPs used in the study. Narrative summary adapted from Rogelj *et al* (2018a) and Bauer *et al* (2017); qualitative assumptions adapted from Riahi *et al* (2018).

	SSP1—sustainability	SSP2—middle-of-the-road	SSP5—fossil fuels & high tech
	Narrative summary		
	Sustainable consumption patterns; low population growth, energy efficiency improving faster than historically; rapid deployment of renewable energy; economic value creation decouples from energy demand; lifestyle changes; social acceptability is low for all technologies (particularly nuclear) except non-biomass renewables.	Societal changes follow established median experience; slow phase out of fossil fuels; energy intensity improvements at historical rates; medium technological improvements; moderate growth of the energy sector; no remarkable shifts in the primary energy mix; continued modernisation of the final energy mix	High-tech yet fossil-fuel-oriented; high energy-intensive lifestyles; deployment of significant amounts of negative emissions technologies and carbon capture for fossil fuels; energy demand strongly coupled to economic growth; social acceptance of new technologies is high except for non-biomass renewables.
Factor	Qualitative assumptions used in the marker IAMs		
Lifestyles	Modest service demand (sustainable consumption patterns)	Medium service demand (societal changes follow established median experience)	High service demand (high energy-intensive lifestyles)
Energy intensity of services	Low (energy efficiency improvements speed up)	Medium	Medium, high for transport
Social acceptance of fossil fuels	Low	Medium (difficult to shut down existing fossil fuels capacity)	High (high-tech yet fossil fuel oriented)
Policies on established and unconventional fossil fuels	Restrictive/very restrictive	Supportive (difficult to shut down existing fossil fuels capacity)	Very supportive
Social acceptance of renewables	High	Medium	Low
Technology development renewables	High (rapid deployment of renewable energy)	Medium	Medium
Social acceptance of nuclear/carbon capture and storage (CCS)	Low	Medium	Medium
Technology development CCS/nuclear	Medium	Medium	High/medium

while there is feasible potential. The variables labelled as 'scenario input…' are those shown in table 3.

3. Results

3.1. Scenarios overview

Table 4 presents key indicators from the three modelled scenarios[3]. Scenario data is calculated from 2010 to the year of net zero[4] or if net zero is not reached then the last year of simulation (2080)—termed 'model end'[5]. In all three scenarios the average annual rate of emissions reductions is too low

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[3] While energy data is usually calculated in units based on Joules, energy data in TEMPEST is calculated in units of tonnes of oil equivalent (TOE), since the historical energy data used to calibrate the model is published by the UK department for Business, Energy and Industrial Strategy (BEIS) in TOE. To compare energy data from IMAGE, in MJ, with that of TEMPEST, IMAGE energy data was converted to TOE.

[4] In this analysis, 'net zero' is considered to be when UK energy-related CO_2 emissions are less than 30 $MtCO_2$/year (derived from the CCC balanced scenario (CCC 2021)). Additional emissions reductions to reach net zero come from mitigation measures not related to the energy system.

[5] There is some overlap between the timelines of the historical and scenario data in TEMPEST. Scenario data starts in 2010 to align with data from IMAGE, but UK historical data is used until 2019.

Table 2. Key concepts and variables in TEMPEST.

Type	Definition
Societal and political concepts	**Political capital** (PolCap) is the potential political power that can be invested in policy formulation and the overseeing of policy implementation processes (Kjaer 2013); in TEMPEST it acts as a kind of 'fuel' for the whole energy transition. **Policy ambition** (PolAmb) is the commitment of government resources to mitigation measure deployment, through different types of policy measures, as taxes, subsidies, and regulation (Hughes and Urpelainen 2015). PolAmb is assigned to each mitigation measure individually. **Public willingness to participate** (PWP) is a combination of 'social capital' (the agency of actors in society to take action (Lin 2011)) and an 'imperative to act' for societal actors, and is used to indicate the likelihood of positive response from society to policies. **Societal pushback** describes negative societal responses to PolAmb. Pushback occurs within feedbacks between policy mixes and socio technical systems (Edmondson *et al* 2019). Support for energy transition can fall when questions of policy implementation arise (Krick 2018), and pushback can happen in particular government departments such as the UK Treasury (Pearson and Watson 2012).
Economy and finance	TEMPEST represents most economic factors, such as technology and policy costs, through simple proxies rather than as monetary costs. The exception is disposable income, which is a data series input; it increases energy services demand (ESD) and the adoption of low carbon technologies in the mass consumer demand sectors including transport and residential. PolAmb is a proxy for the economic cost of policy measures through government budgets. Characteristics of mitigation measures are used as proxies for the marginal abatement cost of technologies: (a) 'novelty and difficulty' increases measure costs; (b) 'international RD&D' (R&D done outside the UK that improves measures) decreases measure costs; (c) user impacts (negative) from mitigation measures are assumed to have no financial cost, but they increase the need for PolAmb to persuade actors to adopt measures
Mitigation measures	There are 39 mitigation measures in TEMPEST. Some are measure types (e.g. residential energy efficiency) and some are specific measures such as natural gas with CCS in the power sector; definitions are provided in (Freeman 2021 b). Measures provide one of four types of benefits: (a) new low carbon energy supplies in the power sector; (b) improvements in end use energy technologies (as energy efficiency or new equipment that enables fuel switching away from fossil fuels); (c) decarbonisation of fuels in demand sectors (e.g. through H2 as an energy carrier and CCS in non-residential sectors), and (d) reductions in ESD across demand sectors (e.g. for heating, lighting, and travel). **Behavioural changes:** 'Behavioural measures' inTEMPEST lead to a reduction in ESD. Behavioural changes in the adoption of demand side equipment, such as electric vehicles, are assumed to occur within the process of measure diffusion and to increase as disposable income increases. **BECCS:** bioenergy with carbon capture and storage (BECCS) is not included as a mitigation measure in TEMPEST due to high uncertainty about its feasibility and thus the difficulty of including it in a simplified and stylised model such as TEMPEST (Quiggin 2021): there are few demonstration plants working, expected costs are much higher than gas with CCS (CCC 2021), there is high uncertainty about importing biofuels and their cost and availability (Clery *et al* 2021), and UK BECCS plants are not expected to come on line earlier than 2035 with slow capacity building (CCC 2020).

to achieve net zero by the target date of 2050[6], and cumulative emissions are higher than the estimated carbon budget[7] by between 13% and 32%. Reduction of the carbon intensity (CI) of power is slowest in SSP5, due to an almost tripling of electricity demand between 2050 and 2080 along with an insufficient addition of low-carbon power sources. Reduction of the CI of non-electric fuels is fastest in SSP5, achieved with decarbonisation of fuels using CCS and H2—measures that receive public opposition in SSP1. In SSP1 and SSP2, average annual rates of emissions reductions are far higher than they were in the historical period, as are rates of relative decoupling of energy use from economic activity (rate of change in energy divided by rate of change in economic activity), and economic activity from emissions.

3.2. Societal and political factors

Figure 2 shows the three main indicators of political and societal factors over time—PolCap, PolAmb, PWP. In SSP1 and SSP2 PolCap increases early on, due to an early positive shock, then a decline occurs as PolCap is used to create PolAmb; and in the final phase there are continual increases in PolCap as the

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[6] The Climate Change Committee defines interim 5 year carbon budgets on the way to net zero, starting in 2008, in addition to the 2050 end target. The interim budgets are not used in this study but are highly influential on energy transition policy.

[7] An indicative UK energy CO_2 budget for 2010–2050, of 10 000 $MtCO_2$, was derived from CCC scenario data (CCC 2021).

Table 3. Summary of inputs to TEMPEST to simulate the SSPs.

	SSP1—sustainability	SSP2—middle-of-the-road	SSP5—fossil fuels & high tech
Political capital	Increases with strengthening drivers, weakening barriers, and a positive 'shock' early in 2020s	Increases slowly over time from increases in drivers and decreases in barriers; small positive shock in mid 2020s.	Decreases slowly over time from small decreases in drivers and increases in barriers.
Population growth by 2080 (on 2010)	26%	23%	48%
Disposable income growth by 2080 (on 2010)	140%	120%	238%
	Percentage adjustments to PolAmb assignment by measures, from historical period		
Branching mitigation measures	50%	100%	200%
Fossil fuel switching measures	500%	50%	33%
Addition of nuclear power	25%	125%	500%
Addition of renewable power	100%	100%	20%
Behavioural changes	500%	53%	67%
Energy savings in industrial sectors	125%	67%	50%

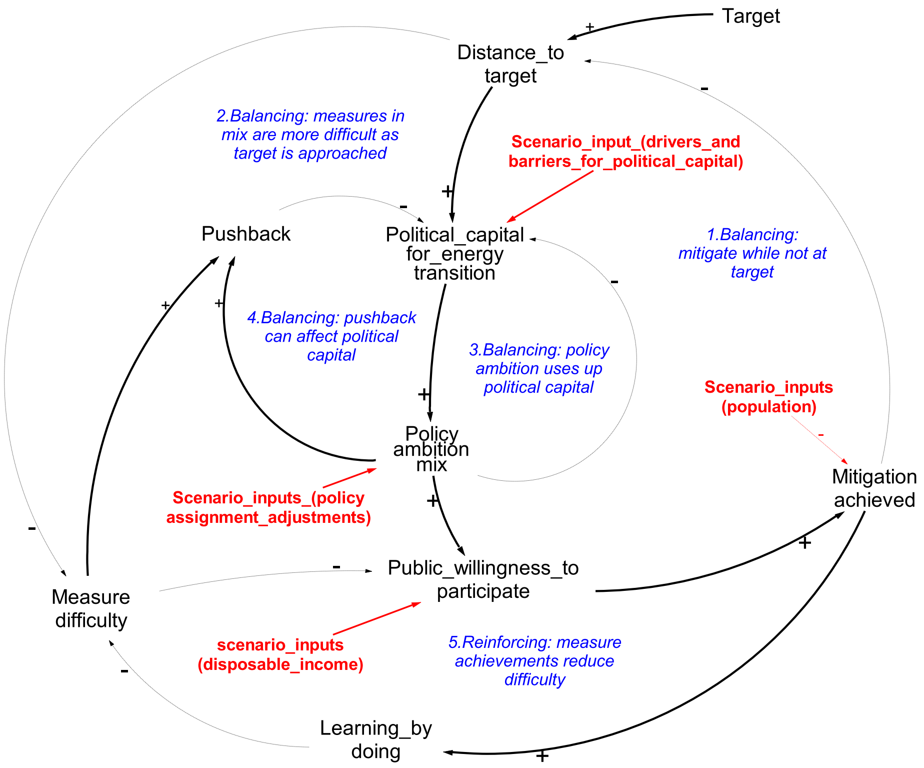
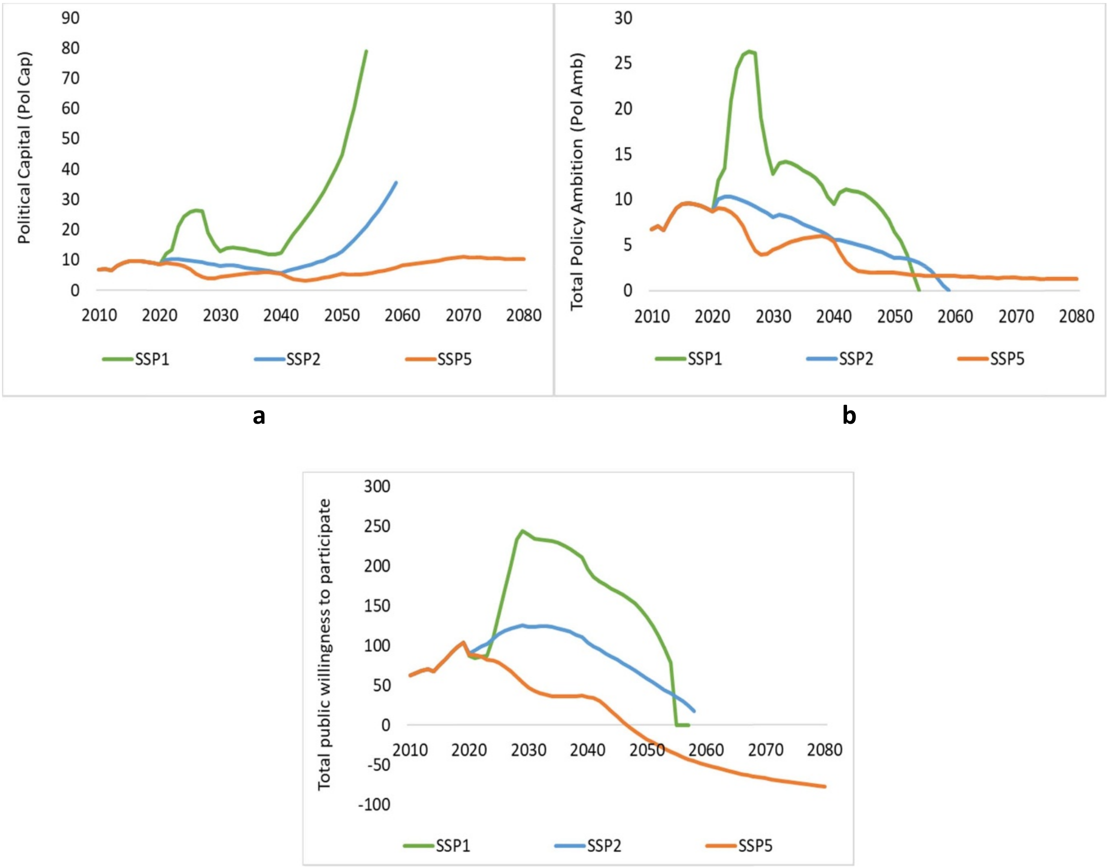


Figure 1. Feedback structure of TEMPEST as a causal loop diagram.

Table 4. High-level indicators from modelling of SSPs in TEMPEST and a historical period.

Scenario values calculated from 2010 to year of net zero emissions or end model run	SSP1 (sustainability)	SSP2 (middle-of-the-road)	SSP5 (fossil fuels & high tech)	Historical (2000–2019)
Year of net zero emissions or end model run	2054	2059	2080	#N/A
Average annual decrease in emissions (kgCO2/cap)	6.7%	6.0%	4.0%	2.6%
Cumulative emissions compared to UK budget ($MtCO_2$)	113%	119%	132%	#N/A
Average rate decrease energy demand (kOE/cap)	2.8%	1.9%	0.5%	0.7%
Average rate decrease emissions from power ($kgCO_2$/cap)	20.0%	12.2%	1.2%	4.6%
Average rate decrease emissions from non-electric fuels ($kgCO_2$/cap)	3.9%	3.9%	5.2%	2.0%
Relative decoupling, economic activity and energy demand	208%	166%	30%	57%
Relative decoupling, economic activity and emissions	497%	523%	230%	202%



a

b

c

Figure 2. Annual political capital (a), total policy ambition, (b) and total public willingness to participate (c).

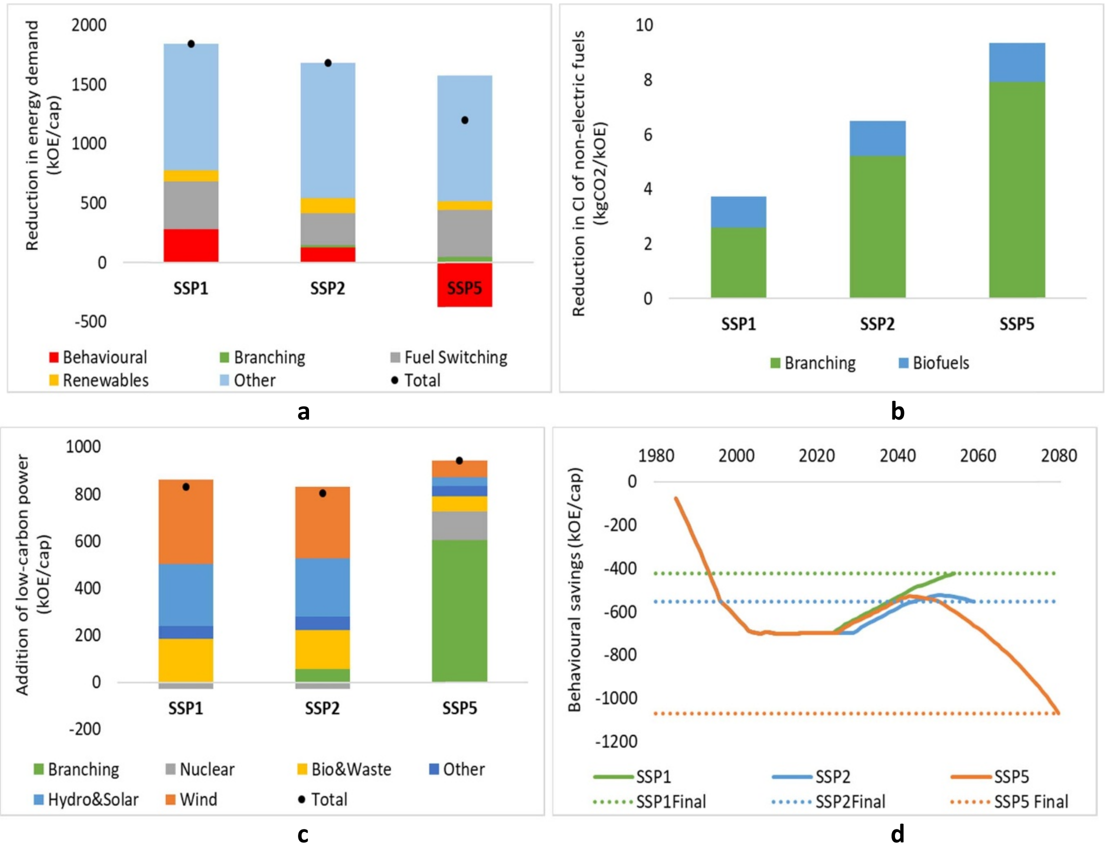


Figure 3. Achievements by types of mitigation measures: energy demand (a), CI of non-electric fuels (b), low-carbon power (c); changes in energy services demand from behavioural measures (d).

political environment remains supportive while less PolCap is needed since the target is being reached. Conversely, SSP5 shows limited PolCap throughout the future period, barely increasing above the level in 2010. Thus, PolAmb is low and decreases over time, meaning that PWP (driven by PolAmb and leaning by doing for measures) falls below zero after 2050 and some measures are no longer deployed.

3.3. Mitigation measures

Figure 3 shows cumulative mitigation achieved from different types of mitigation measures, 2010 to model end. The preference for high-tech solutions in SSP5 is seen in high deployment of 'branching' (high complexity and novelty) measures in low-carbon power, less renewables or fuel switching, and increasing ESD. Conversely, SSP1 includes decreased ESD, highest addition of renewables in the power sector and the lowest decarbonisation of non-electric fuels with branching measures. Figure 3(d) shows trends in total ESD. ESD grows steadily between 1980 and 2010 (i.e. there were negative behavioural energy savings), decreases after 2020 according to the prioritisation of behavioural measures in each narrative, and increases again after 2050 in SSP2 (although slightly) and SSP5. Levels of ESD in SSP1 and SSP2 by the model end are in line with those last seen in the 1990s.

3.4. Total cost of scenarios

A 'whole society' estimate of the total cost of mitigation was calculated as a combination[8] of total policy cost, total societal cost (effect on lifestyles), total cost of measures in demand sectors, and total cost of measures in the power sector[9]. The total cost of scenarios (figure 4) is highest in SSP1, 33% lower in SSP2 and 50% lower in SSP5. SSP1 includes high social and policy costs and high costs for new low-carbon power sources (mostly renewables),

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[8] Since the total cost combines values with different units, it was necessary to even out their contribution to the total cost to be able to compare scenarios. A scenario weighting factor was calculated for each scenario as the ratio between the sum of total policy cost and lifestyle cost with total monetary cost for supply and demand measures. The average of the three scenario weighting factors (16%) was then applied to the monetary costs to bring them into a similar range to policy and lifestyle costs.

[9] Total policy cost is the total PolAmb assigned to all measures (in units of PolAmb/model year). Total societal (lifestyle) cost is the decline in ESD through behavioural measures (in units of kOE/cap/model year). Total economic cost is a high-level estimate in units of £B. For demand measures, the marginal abatement costs of measures in £/tCO2e in 2050 (CCC 2021) is combined with total measure savings in tCO_2 from 2010 to model end. For power sector measures, the cost of generation of low-carbon power measures, in £/MWh in 2050 (CCC 2021), is combined with the total MWh added from 2010 to model end, for each measure. Behavioural measures are assumed to have no economic cost or benefits. No policy benefits other than emissions reductions are included.

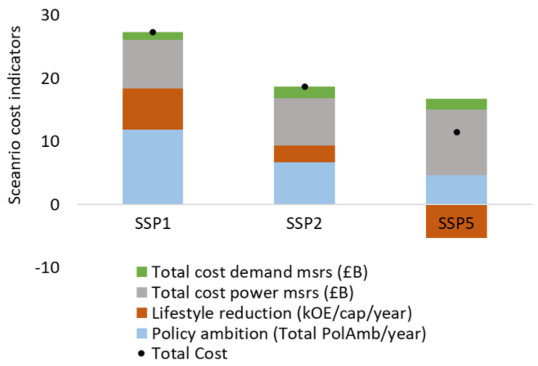

Figure 4. Total cost of mitigation as political, social, and economic.

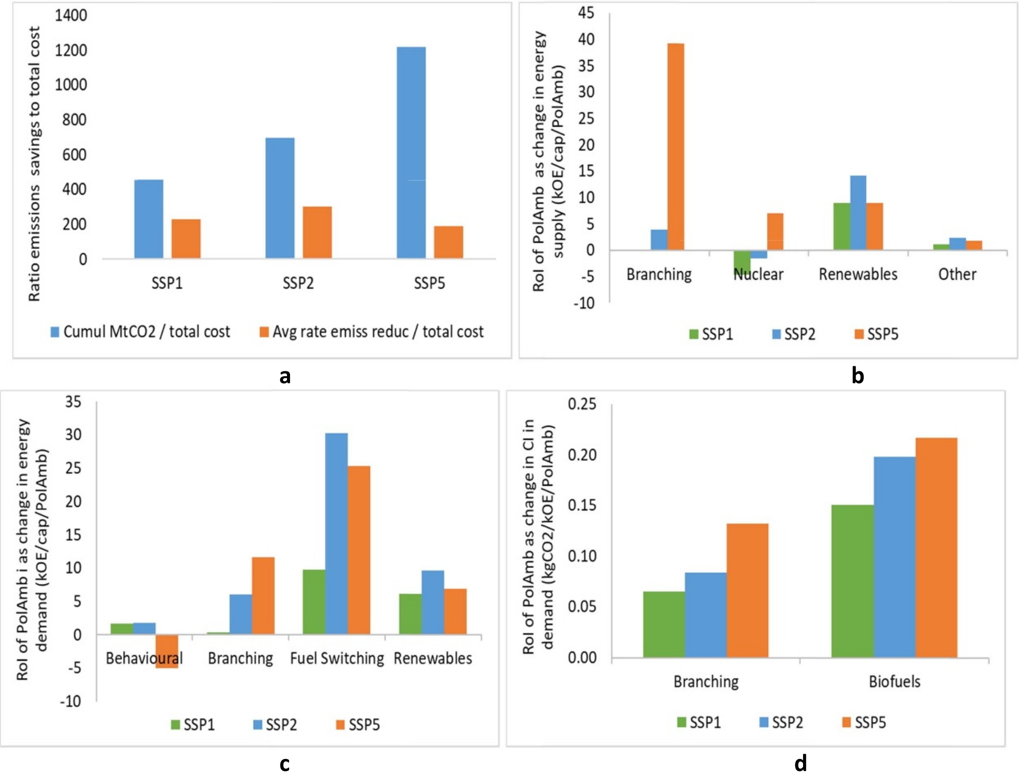

Figure 5. Return on investment (RoI) of policy ambition for categories of mitigation measures: energy supply (d), energy demand (e) and carbon intensity of non-electric fuels (f).

while SSP5 has the highest spending on power sector measures and negative lifestyle costs (i.e. ESD increases). SSP2 costs are the most balanced mix.

3.5. Efficiency of the scenarios

Figure 5(a) shows the ratio between total scenario cost and cumulative emissions or average annual rate of emissions reductions. These values are indicators of the overall efficiency of achieving emissions reductions under the scenario narratives. The ratio is best for SSP1 for limiting cumulative emissions (i.e. lowest) and best for SSP2 for average annual rate of emissions reductions achieved (i.e. highest). Both ratios are significantly worse in SSP5. Figures 5(b)–(d) show the return on investment (RoI) from PolAmb for categories of mitigation measures. The RoI is the ratio between the PolAmb applied to promote mitigation measures and the energy savings or CI reductions achieved through the measures. RoI is an indicator of the efficiency of policy investments. Where RoI is negative, there is a net reduction in mitigation despite PolAmb being applied. Negative RoI is seen for nuclear power in SSP1 and SSP2, as low societal acceptance prevents new nuclear build despite there being some PolAmb, and for behavioural measures in SSP5 due to the societal expectation

Table 5. Key differences between TEMPEST and IMAGE that influence energy transition modelling.

Difference	TEMPEST	IMAGE
The model scale	National	Global (with regions)
Calculation of ESD	Endogenous, influenced by input trends of disposable income and PolCap drivers and barriers	Input-driven
Inclusion of negative emissions technologies such as BECCS	Not included	BECCS causes negative power sector emissions after 2040
Representation of policy	Measure-specific	Policy can be represented in several ways, including as a global carbon price which is used as a shadow price for mitigation measures, focused on the stated aims of policies, or representing the exact policy instrument and targeted measures (36).

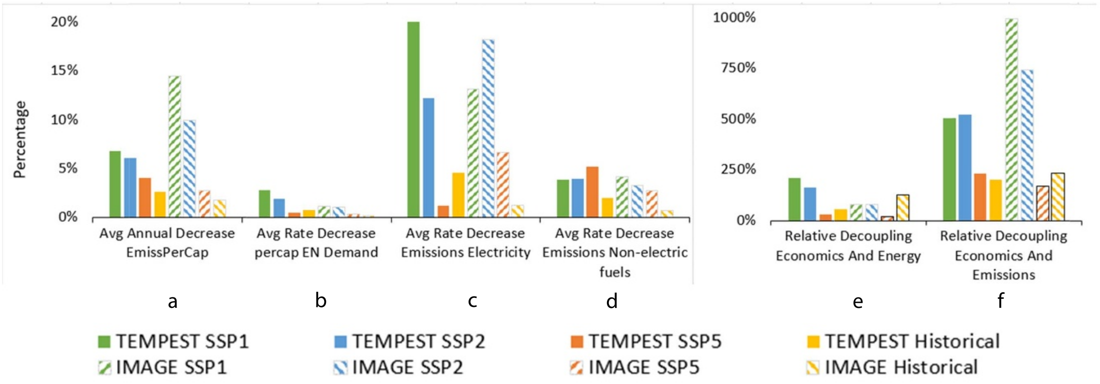

Figure 6. Average annual decrease in key indicators from TEMPEST and IMAGE, from 2010 to model end, as: per capita emissions (a), per capita energy demand (b), emissions from electricity, (c) emissions from non-electric fuels, (d) relative decoupling between economic activity and energy use, (e) relative decoupling between economic activity and emissions (f).

that energy transition should not limit lifestyles. The highest RoI in energy demand is for fuel switching in SSP2, followed by branching low-carbon power measures in SSP5.

3.6. Comparison of SSPs modelled in IMAGE and TEMPEST

The IAM used for comparison is IMAGE, which is documented in the literature and on the IMAGE webpage (van Vuuren *et al* 2021, Edelenbosch *et al* 2018, van Beek *et al* 2020, PBL 2022). Modelling of SSPs in IMAGE (Stehfest *et al* 2014) is achieved through introducing sets of exogenous drivers that include '*interpretations of the technology, lifestyle and policy elements of the SSP narratives*' (Bauer *et al* 2017)—including ESD and technology learning curves, and trends in population and GDP. It was not possible to make a detailed comparison between SSP scenarios from TEMPEST and IMAGE since the models are fundamentally different in their logic, scale, level of detail, and assumptions. Where IMAGE and TEMPEST do cross over, however, is that both model future energy demand, energy supply, and energy-related CO_2 emissions in the UK[10]. Key model differences are shown in table 5.

Figure 6 shows results of a high-level comparison of trends in key indicators from IMAGE and TEMPEST, for the same scenarios and under a similar emissions target[11], as average annual decrease between 2010 and model end[12]. For most of the indicators and in both models, historical rates of change

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[10] Data from IMAGE is for the region of Western Europe, which is used as a proxy for the UK.

[11] IMAGE data used in this study is as follows. Data for Western Europe, for models runs that have global radiative forcing limits set at the lowest that exists for each SSP: 1.9 W m^{-2} for SSP1 and SSP2, and 2.6 W m^{-2} for SSP5. Data downloaded from the USS data download facility for IMAGE 3.0 (Stehfest *et al* 2014), https://models.pbl.nl/image/index.php/USS_manual.

[12] In both models, 'model end' is the year of reaching net zero emissions or 2080, whichever comes first. For comparing the CI of electricity and non-electric fuels, the model end is considered to be the year that the CI reaches zero or 2080, whichever is first. When comparing outputs from TEMPEST and IMAGE, values are expressed in generic per capita units or percentages, to eliminate the influence of other model differences such as population.

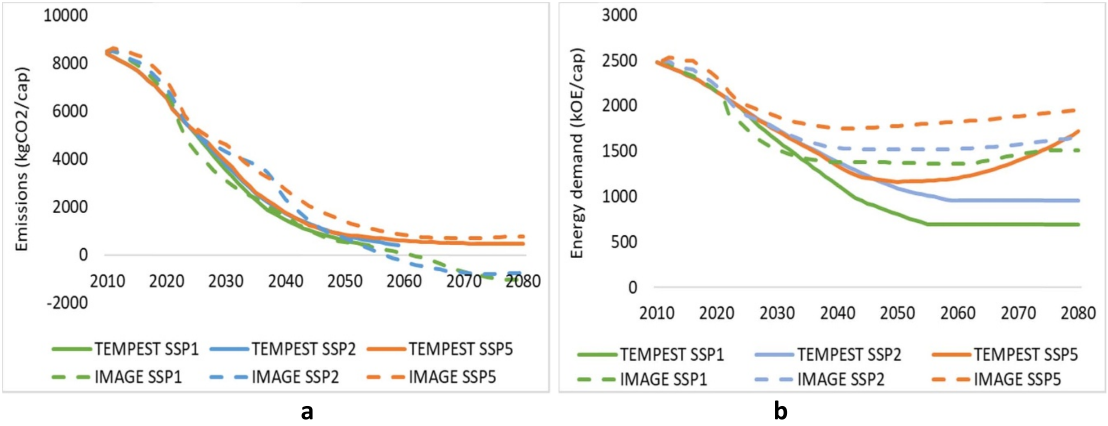

Figure 7. Emissions (a) and energy demand (b) results from TEMPEST and IMAGE.

are much lower than future ones, indicating the very challenging rates of change needed compared to the past. IMAGE generally achieves higher emissions reductions (influenced partly by BECCS), while the same scenarios in TEMPEST achieve higher energy demand reductions. This trend is in line with (Brutschin *et al* 2021) who state that '*the power of demand-side changes might be underexplored in existing IAMs scenarios*'.

The pace of change in emissions is similar between the models up to around 2060, with SSP5 levelling off at above zero in both models (figure 7(a)). There are stronger differences between the models in the energy demand data (figure 7(b)), with TEMPEST scenarios showing a wide spread of values while energy demand in IMAGE shows a similar pattern across scenarios. Additional comparison results are in the SI, section 3.

Additional comparison graphs and commentary on differences in the treatment of policy are in the SI, section 3.

4. Discussion and conclusions

4.1. Feasibility of SSP scenarios as modelled in TEMPEST

4.1.1. Key uncertainties arising from the modelling methodology

While there are numerous aspects of the modelling methodology that contribute to uncertainty about outcomes, three are key to the feasibility question.

(a) TEMPEST runs continuously from 1980 to model end, and the structure and endogenous dynamics of the system are assumed to remain the same throughout. Calibration of the model to historical energy and emissions trends (described in the SI of (Freeman 2021)) is assumed to give the model a grounding in real-world energy system change in the UK. Future changes are assumed to occur within basically the same political-societal-technological system, even though this may not be the case.

(b) PolCap is a pivotal variable in TEMPEST simulation. Without enough PolCap, the whole energy transition is underpowered and too slow. Setting inputs for the scenarios (table 3) so that energy transition and measure achievements are in line with the scenario narratives led to PolCap being 250% (SSP1) and 50% (SSP2) higher in the future period than the historical one. Whether this magnitude of positive political change with regard to energy transition is feasible is highly uncertain.

(c) Measures with the highest uncertainty are those that are technologically difficult and/or novel (branching) and those that could disrupt societal lifestyles (behavioural)—since there is little historical precedent for their deployment at scale. The model relies on numerical characterisations of these measures to reflect their technological and/or societal difficulty; if values are set too low (measures are modelled as easier than in reality) or too high (measures are modelled as more difficult than in reality), then the simulated pathway will over- or under-estimate their likely rate of deployment.

4.1.2. Feasibility of scenarios

Historical precedent is a major consideration for discussing feasibility—if it has happened before then it could again (Jewell and Cherp 2020). Based on this premise, at the global scale the evidence is not encouraging. For example, (a) when mitigation scenarios are constrained to historical rates of change the best achievable limit to temperature rise is 2.1 °C (Napp *et al* 2017); (b) most global modelled scenarios include improvements in energy intensity that are historically unprecedented (Loftus *et al* 2015); (c) little empirical research exists that quantifies the role of governance capacity in implementing climate policies, yet the institutional dimension is the largest feasibility concern for global mitigation scenarios (Brutschin *et al* 2021). Some particular observations about the three modelled scenarios for the UK follow.

The contribution of the demand side in UK climate mitigation is crucial (Lees and Eyre 2021) and in SSP1 there are significant decreases in ESD after 2020 with the final level of ESD about the same last seen in the mid 1990s—politically a very difficult proposal for any government. SSP1 would only be feasible with a transformative change in the way society consumes energy, which in theory could be achieved through demand-side innovation—such as outlined in the scenarios 'digital society' and 'collective society' in (Le Gallic *et al* 2017). On the other hand, SSP5 includes large amounts of mitigation from nuclear power and from new and complex branching measures, including H2 in demand sectors, CCS in industry and the power sector, and electrification of air transport. So far, CCS programmes have produced poor results: '*CCS will not advance without significant public investment and the required support policies will not be put in place without political support*' (Lipponen *et al* 2017). Furthermore, new nuclear power and gas with CCS in the power sector are expected to have double the levelised cost of variable renewables in 2050 (CCC 2021). Based on the decades that were needed to build the UK nuclear industry, starting in the 1970s (a comparably novel and complex technology at that time), the required rate of development of branching measures in SSP5 is unprecedented. SSP2 includes a more moderate amount of ESD reduction compared to SSP1, although still ending up significantly lower than in 2020, and a more moderate addition of mitigation from branching measures compared to SSP5. SSP2 is the most efficient in terms of average annual emissions reductions per total cost. Based on these metrics, SSP2 appears to be the most likely out of three modelled scenarios to be feasible.

4.1.3. Feasibility of achieving energy transition targets

The current UK energy transition strategy lays out the following vision: '*In 2050, we will still be driving cars, flying planes and heating our homes, but our cars will be electric…our planes will be zero emission allowing us to fly guilt-free, and our homes will be heated by cheap reliable power drawn from the winds of the North Sea*' (BEIS 2021). Britain's 2022 energy security strategy envisages an affordable, clean, and secure energy system achieved through improved energy efficiency, a fleet of new nuclear power stations, large additions of solar and wind power, and use of hydrogen (HM Government 2022). The narratives in these two UK strategies include key aspects of the SSP5 narrative: no negative effects on lifestyles, new nuclear power, fossil fuels and biofuels with CCS in the power sector, and decarbonisation of air travel. They include, however, considerable amounts of offshore wind and a push on energy efficiency which are more aligned with SSP1 and SSP2. Overall, of the three modelled scenarios, current UK strategy appears to be the most aligned with SSP5. Modelling of SSP5 with TEMPEST indicates a low likelihood the UK will achieve its net zero target by 2050, indicating that significant real-world improvements will be needed in the key SSP5 assumptions that limit the rate of mitigation—in particular, speeding up deployment of branching measures, preventing an increase in ESD after 2050, and increasing PolCap for energy transition from 2020 onwards.

4.2. Use of TEMPEST findings in IAMs

Three recommendations are made here on how findings from TEMPEST might be used in IAMs[13]. They are made with acknowledgment that introducing these new concepts and calculations into IAMs may not be worth the additional computational complexity; and that the fundamental differences in model design between TEMPEST and IAMs could mean that it is impossible to justify transferring casual relationships between variables in TEMPEST to be used in IAMs. The recommendations make use of approaches to linking insights from social sciences to IAMs, as described in (Trutnevyte *et al* 2019), which are: 'bridging' (limited interactions around shared concepts), 'iterating' (social science findings are translated into quantitative input assumptions used by IAMs), or 'merging' (integrating societal factors into the design of IAMs).

4.2.1. Political and societal support for energy transition

IAMs generally assume that enough social and political support will be available. '*Modelled energy transition pathways assume broad social acceptance…and limited political inertia or institutional barriers*' (Rogelj *et al* 2018b). IAMs have been critiqued for a lack of representation of uncertainty about the achievability of societal targets (Keppo *et al* 2021). TEMPEST scenarios link social and political support for energy transition to emissions reductions, and to the deployment of different types of mitigation measures such as renewables and nuclear power.

Recommendation is to establish an iterating link that translates the results from TEMPEST into quantitative input assumptions that can be used in IAMs. The key result to share between models is the relative influence of political and societal support on the deployment of different types of mitigation measures for energy transition. Specifically this data could be used in IAMs to set a range for the uncertainty in achieving emissions reductions from policy interventions such as carbon prices and spending on policies.

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[13] While most IAMs are global, TEMPEST models only the UK energy transition and only CO_2, so its findings are probably only relevant for those parts of IAMs that model nations or regions with a similar energy system maturity as the UK and a similar type of economy.

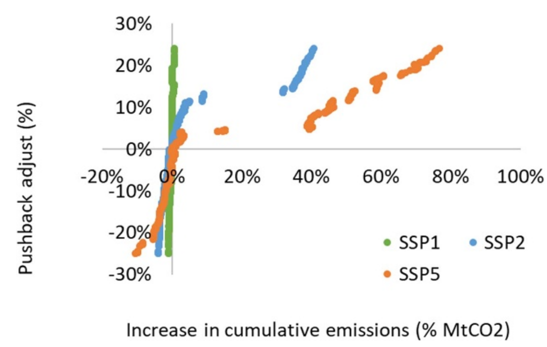

Figure 8. Variations in pushback strength in TEMPEST scenarios and effect on cumulative emissions.

A set of variations in societal and political indicators linked to their influence on energy demand reductions or low-carbon power additions can be provided from TEMPEST.

4.2.2. The impact of societal pushback

TEMPEST includes the effects of societal pushback (explained in table 2), which reflects what is politically feasible within different scenarios. This is a difficult concept to quantitatively model yet its effect has been seen in many countries in response to specific policies and/or rising fuel prices. The importance of pushback is likely to increase in future, as the more transformative parts of energy transition cause deeper disruptions to economy and lifestyles. A sensitivity test in TEMPEST that varies the strength of pushback by ±25% (figure 8) shows little effects on emissions in SSP1 but significantly higher emissions in SSP2 (up to 40% increase) and SSP5 (up to 75% increase) when pushback is adjusted upwards (although little decrease in emissions when pushback is adjusted downwards). This illustrates the possible magnitude of emissions uncertainty caused by pushback. Pushback is generally not included in IAMs, and there is probably no easy way to add it since (at least according to the theory of TEMPEST) it requires modelling a feedback between PolAmb, mitigation measure implementation, and PolCap.

Recommendation is to create a bridging link that simply shares concepts. The theory, modelling approach and results regarding the modelling of pushback from TEMPEST can be provided to IAM modelling teams.

4.2.3. Energy services demand changes

In IAMs, ESD is typically exogenously introduced as a driver and there is an endogenous response to energy prices. The parameters for introducing different approaches to reducing energy demand (e.g. 'avoid, shift, improve' (Creutzig *et al* 2018)) are determined using decomposition analysis. IAMs may not always disaggregate ESD from other measures that reduce energy demand such as energy efficiency and may not always include specific policy measures that influence ESD. Patterns in ESD may change in the future, influenced more by factors other than the price of energy, and a changing economy under energy transition could provide more potential for niche social innovation in energy service provision (Magnani and Osti 2016). TEMPEST's endogenisation of the calculation of ESD in response to the influence of affluence, behavioural policies, and the user impacts of particular measures, allows for testing interventions that affect ESD within the model and better alignment with scenario narratives on public attitudes to sustainable consumption. ESD is found to be a highly influential factor in achieving net zero across TEMPEST scenarios. However, social innovation is not currently included in TEMPEST.

Recommendation is for a bridging link that shares concepts about how ESD changes under the influence of a range of factors not usually included in IAMs. IAM assumptions about avoid, shift improve behaviours that impact ESD could be adjusted to also include causal links to disposable income, type of measure, public willingness to participate and the sometimes negative user impacts of measures. This could improve uncertainty testing for modelled changes in ESD and energy behaviours.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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