Behavioural Evidence and Analysis for Net Zero: Summary of Methodological Scoping Study

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Contents

Glossary

Glossary of acronyms

- WESM: Whole Energy System Modelling/Model
- ESD: Energy Service Demand
- ESME: Energy System Modelling Environment
- NTM: National Transport Model
- NHM: National Housing Model
- EDM: Energy Demand Model
- EEP: Energy and Emissions Projections
- GHG: Greenhouse Gas(es)
- DDM: Dynamic Dispatch Model
- MCA: Multi Criteria Assessment
- ABM: Agent-Based Model
- CGE: Computable General Equilibrium (model)
- MACC: Marginal Abatement Cost Curve
- UKTM: UK TIMES Model
- QUALY: Quality Adjusted Life Year

Glossary of terms

- Endogenous: in the WESM context this refers to a system feature that is determined **by** the WESM
- Exogenous: in the WESM context this refers to a system feature that is determined (i.e. assumed) **outside of** the WESM
- Intangible costs: a catch-all term for monetising of “non-market” drivers and barriers, such as valuation of individual’s time, physical space or risk
- Hurdle rates: generally this represents the minimum return an investor would require over the investment lifetime. In the WESM context this captures the opportunity cost of capital for a stakeholder making an energy investment (implemented as the rate at which investments are assumed to be amortised)
- Policy costs: these represent the direct costs associated with any specific policy enacting in support of energy system transition, e.g. the costs to design and administer subsidy schemes
- Optimisation model: in the current context this refers to a class of mathematical models that perform a minimisation or maximisation of a cost metric subject to constraints, typically facilitated via commercial solver software

Executive Summary

Executive Summary

- Several internal HMG experts (modellers, economists, sector experts, policy teams and social/behavioural scientists) were interviewed on the subject of *how they interact with Net Zero pathway design* for this project. Subsequently, experts from the modelling and socio-technical transitions community (mostly academic) were interviewed, with the questioning influenced by the responses provided by HMG. In parallel, a focused literature review of modelling and analytical methods was carried out.
- A key focus of this study was on **the usage of whole energy system models (WESMs),** and how (if at all) consumer behaviour is included within pathway design, with particular emphasis on optimisation models such as UK TIMES used within HMG, rather than models used to evaluate policy
- There was general agreement amongst the interviewees that **the role of societal change has been under-represented in prominent scenario studies**, in part because of the technical challenge of incorporating behaviour within the prominent WESMs. ESD assumptions and forward-looking assumptions are often deeply embedded within scenarios and are not transparent to the reader. The COVID-19 pandemic has highlighted a lack of confidence in some of the existing assumptions around ESDs and the extent to which social norms can change.
- However, adding increasing sophistication *into* models (e.g. endogenous behaviour) is not always apt; evolution of modelling practice by using different tools at the right time & in the right way may be more appropriate. There was discussion around specific use of the incumbent WESMs, their focus on the supply-side and how best to include this within pathway design.
- Energy scenario studies tend to highlight **preferred energy system (pathway) designs and decarbonisation profiles**. Decarbonisation costs are sometimes but not always presented, and typically neglect costs not internalised in models, such as policy or intangible costs; scenarios are thus difficult to compare holistically. An emerging area of interest is to consider **multi-criteria analysis of scenarios** rather than to simply present standard results of models along with narrative. MCAs offer the ability to correct for "non-market" quantitative metrics (including policy costs and intangibles) as well as more qualitative metrics (including levels of societal change) when assessing the overall "costs and benefits" of a pathway.

Study aims and methodology

Aims of Work Package 3

- To summarise the **shortcomings in the representation of societal / behavioural change** in whole energy system models*
- To assess the potential **benefits of addressing these shortcomings**
- To offer a review of the **key challenges of implementing social / behavioural change**
  - Within models
  - Alongside models
- To summarise **options for consideration** for HMG to implement
- To provide a **recommendation for development** in Work Package 4

* Focus predominantly on optimisation-based models in wide use, but capabilities of different types of models is also of relevance

Research questions

RQ2.1: How can different levels of (positive and negative) societal change affect the deliverability, costs and benefits of reaching net zero?

RQ2.2: What are the current methodological limitations and challenges in incorporating evidence on societal change into whole system/energy pathway planning and modelling (e.g. modelling pathways to net zero)?

RQ2.3: What methodological frameworks/approaches could be adopted to better assess the impact that societal change could have on the deliverability of net zero? (these could consider both quantitative whole-system planning / modelling techniques and alternate approaches such as more qualitative/descriptive scenario assessments or multi-criteria analysis).

Addressed within BEANZ WP3

How are we distinguishing behavioural versus societal change in this project?

- In this study, behavioural changes are considered to be individual behaviour and lifestyle changes (such as individuals switching to electric vehicles for transportation, installing an air source heat pump for domestic heating or turning a room thermostat down by 1 °C). These individual behavioural changes could be habitual or one-off decisions/purchases. In many cases, these individual behaviours are influenced by wider societal changes.
- Societal change covers aspects such as the makeup of society (population growth, ageing population, etc.) and changes in social norms (increased home working, greater prevalence of service-oriented transactions rather than item purchases, etc.). Some shifts in social norms can have quite radical effects on the way people could live and work. For example, a shift in working practices from office-based to home-based will potential affect the energy consumption characteristics, affecting transport demands and energy consumption trends in homes and offices.
- From an energy modelling point of view, radical societal shifts such as the working practice example are likely to be best considered with regards to their impact on different energy service demands (ESDs). Within this report we discuss the concept of exogenous ESDs, and careful consideration of ESDs as a group under a common societal narrative is an appropriate way to think about societal change. Behavioural change, on the other hand, needs to be consistent with the underlying societal narrative – for example, uptake rates of new technologies should be reflective of the society envisioned (politically, economically etc) and of the barriers or enablers of investment in low carbon technologies.

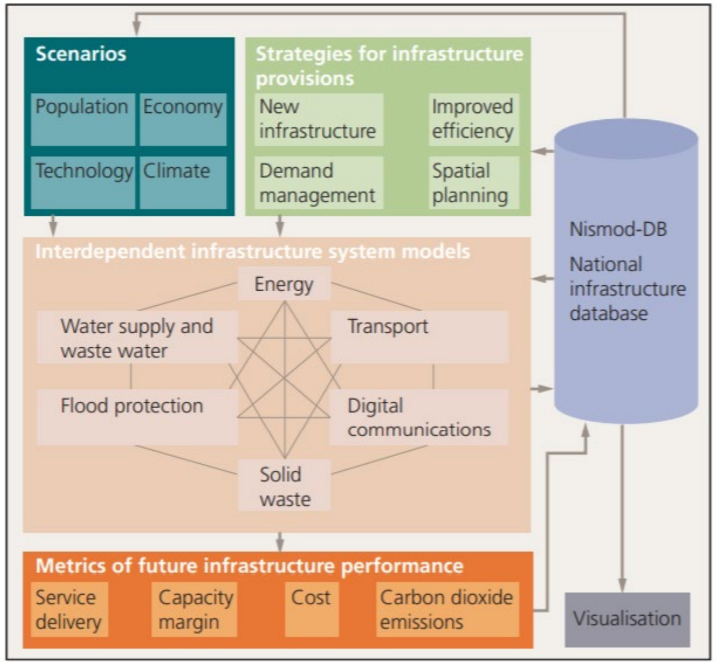
Methodology followed for scoping study

The approach adopted for this scoping study was as follows:

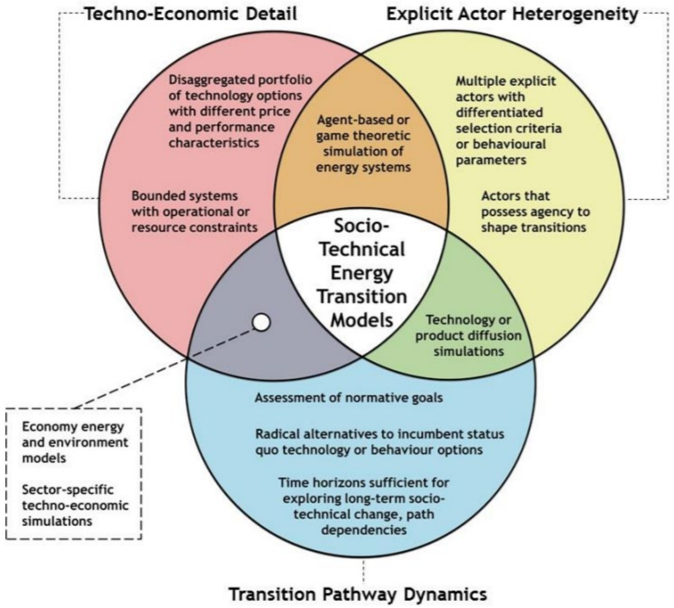
1. Definition of the evidence assessment protocol
2. Identification and interview of ten HMG experts to inform and advise WP3 on current practices and perceptions
3. Bounded, search string-based review of evidence in literature
4. Identification and interview of seven additional external experts to inform and advise WP3 on other methodologies*
5. Analysis of key sources of evidence
6. Synthesis of findings into summary material
7. Recommendations for WP4

* In many cases, experts preferred not to be personally linked to any opinions or evidence offered, except where referring to their own published work. As a result, a philosophy of non-specific attribution is generally applied within this work package

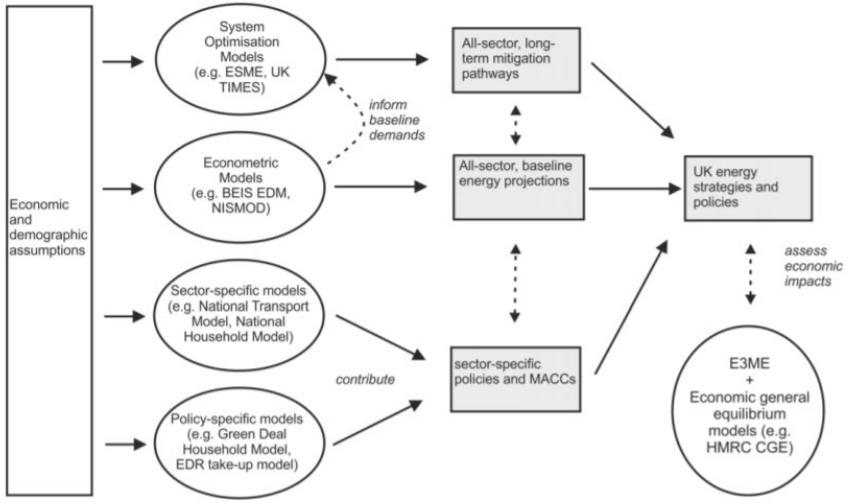
Examples



J. W. Hall et al., "Strategic analysis of the future of national infrastructure," *Proceedings of the Institution of Civil Engineers – Civil Engineering*, vol. 170, no. 1, pp. 39-47, 2017 [1]



F. G. N. Li and N. Strachan, "Take me to your leader: Using socio-technical energy transitions (STET) modelling to explore the role of actors in decarbonisation pathways", *Energy Research & Social Science*, vol. 51, pp67-81, 2019 [2]



L. Hardt *et al*, "Modelling Demand-side Energy Policies for Climate Change Mitigation in the UK:: A Rapid Evidence Assessment", *UKERC Working Paper*, February 2019 [3]

Decarbonisation pathway design in HM Government and other groups

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- Role of whole energy system models notable in helping design pathways to Net Zero and previous targets
- UK TIMES is a key WESM used in BEIS and elsewhere to ensure pathways envisioned are consistent with GHG targets and ensure energy balance, resource availability etc
- Detailed sector-level feeder models provide a source of information to WESMs. Expert engagement used as input and evaluation of model
- Pathways often focus on technical solutions:
  - **Hindcast-based**: focused on pathways that *must* achieve a specific outcome (e.g. meet carbon budgets at lowest cost)
  - **Supply-side focus**: demand-side options included but not often as extensively as supply-side (and often mediated by technology)
  - **Descriptors**: summary costs typically offered as metrics (e.g. x% of GDP) are technical, physical costs
  - **Techno-optimism**: often assume successful technical innovation and careful practice is needed to ensure input/output consistency

Overview of the methodology used to develop 2050 pathways

The 2050 analysis uses UK TIMES, a model of the whole UK energy and greenhouse gas system covering the period 2010 to 2060[347].

The technology pathway identified by the model will vary according to the input assumptions for technology and resource performance, cost and availability. The model can also be set up to roll out specific technologies in line with a given deployment profile. When the model is used in this way it will take account of the deployment profiles for specific technologies, and identify the least cost mix of remaining options.

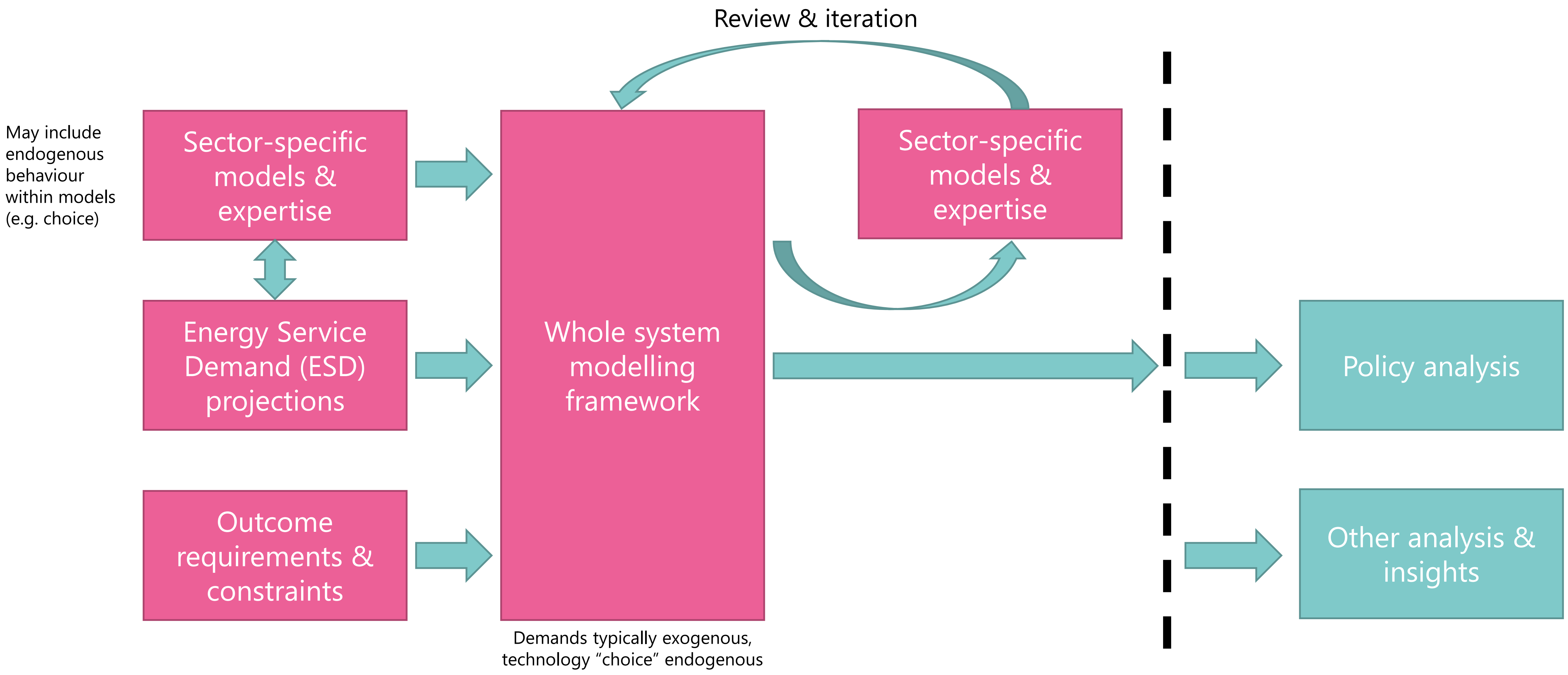
Second, it confirms all of the pathways are consistent with meeting the 2050 and fifth carbon budget emissions reduction targets.

The modelled pathways were constructed in UK TIMES by varying input assumptions for:

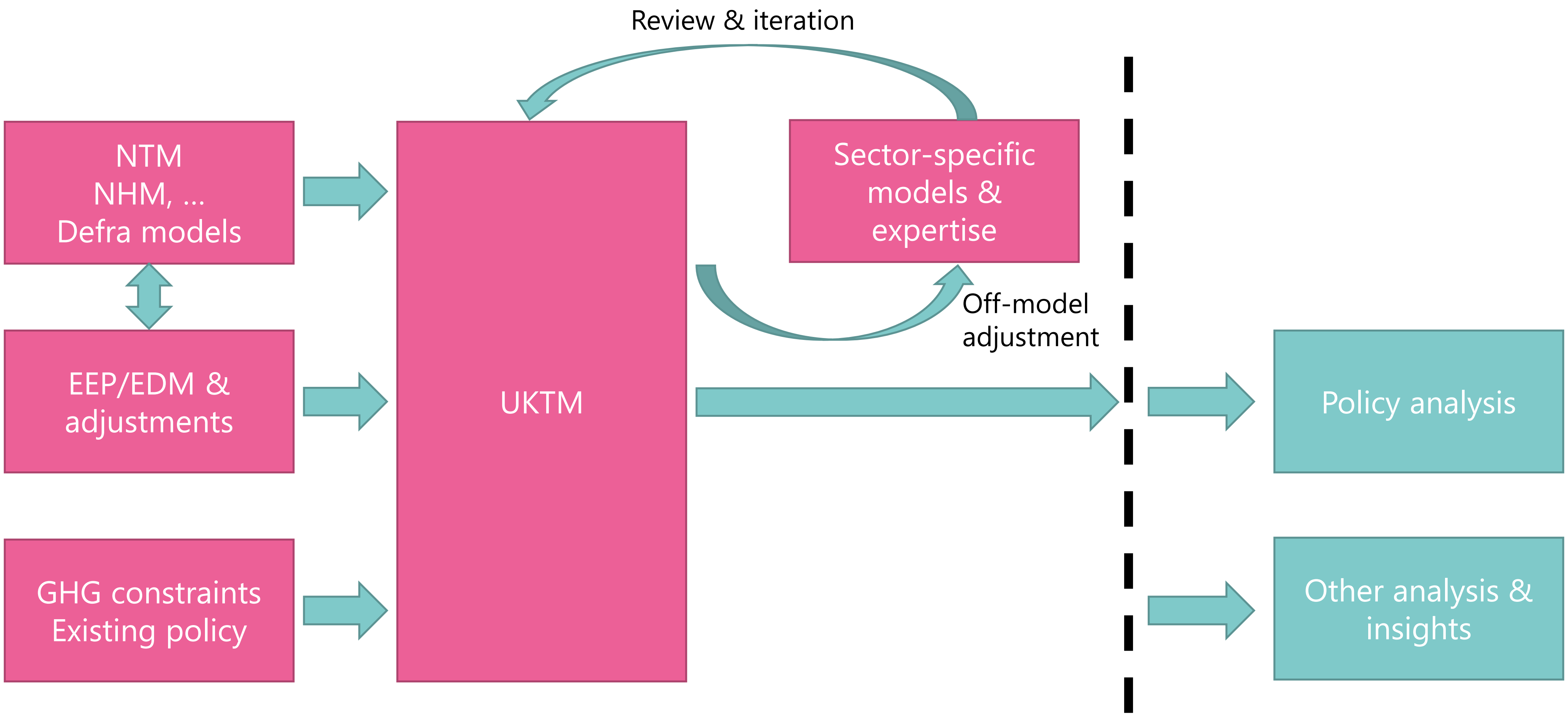
- Availability of technologies. For example, CCUS is not available in pathway 1 and negative emissions technologies are only available in pathway 3.
- The extent or speed at which technologies can be rolled out e.g. faster growth in hydrogen production is allowed in pathway 2, whilst expansion of electric heating is more restricted.
- Entering fixed deployment profiles for some technologies e.g. 100 per cent of cars and vans are set to be powered by electricity or hydrogen in pathways 1 and 2 respectively.

Example pathway development approach (The Clean Growth Strategy, pp153)

Energy system models play a key role in designing decarbonisation pathways



HMG follow a similar process when developing pathways



Treatment of behaviour of energy actors varies across key HMG models discussed with HMG experts

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UKTM	Transport	Land use	Power generation
Least-cost whole system optimisation model, providing system designs and pathways consistent with GHG targets	National transport model includes logit choice model, trip time features, extensive segmentation	Plausible land use scenarios developed accounting for behaviours beyond simply techno-economic (e.g. decision maker knowledge, attitudes to change etc)	DDM includes some shiftability of demand, variable technology hurdle rates
May include ability to time-shift demand: behaviour as “inherently flexible” demand May include ability to avoid demand: price elasticity	May include ability to “avoid” consumption: via mode-shifting to active transport etc	May include ability to avoid emissions: via land use/forestry scenarios	May include ability to time-shift demand: via technologies/DSR May include ability to avoid consumption: via DSR

Technical limitations* of WESMs within existing pathway modelling process

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Limitation	Commentary	Potential resolutions
Projection and interpretation of exogenous ESDs	Behaviour/change rolled up into highly aggregated quantities (e.g. *annual passenger-km*), often derived (e.g. via macroeconomic drivers) outside of the WESM; modelling considers fixed ESD trajectories Unclear what magnitude of behaviour change, if any, is implied in any given ESD May emphasise a "static" depiction of the energy system	Transparent, detailed and adaptable off-model description of end-use demands for a wide variety of stakeholders Application of on-model endogenous demand response
Exogenous technology cost assumptions	Linear WESMs require prescribed cost and efficiency profiles – not conventional exponential learning rates. Can lead to inappropriate deployment behaviours (e.g. switch-over rates) and neglects feedback as driver to technology improvements	On-model inclusion of endogenous technological learning Practice and process: detailed review and analysis of deployment versus cost/efficiency to ensure internal consistency; use of probabilistic study
"Designer's optimal view" with perfect foresight	Whole-system cost optimisation of typical WESMs ➔ model output optimal for a *hypothetical system architect*, not for individual stakeholders	Post-modelling analysis of pathways from multiple diverse perspectives Greater model granularity (e.g. socio-economic groupings) with differential costing/hurdle rates Adopt a different decisioning methodology (e.g. ABM or myopic optimisation) or link other models
Limited macro-economic context	Different energy system scenarios produced through modelling may have radically different features from the point of view of the whole economy	Combining of whole energy and whole economy (CGE) models for candidate scenarios (soft or hard-linking) Post-modelling synthesis of economy-focused insights and metrics (e.g. supply chain)
Engineering-centred uptake constraints	Technology uptake with WESMs bounded by engineering/supply-chain constraints (build rates and growth of rates). Normative – societal challenge of uptake of particular technologies not always detailed	Deeper analysis of implied uptake profiles and evaluation against social data (trials, recent history, analogous transitions etc) Application of further constraints/cost uplifts to include societal barriers
Technical cost focus of modelling	Outputs of models are system costs/welfare, or costs relative to a counterfactual (existing policy, no decarbonisation). These neglect some wider energy system-related costs (e.g. air quality impacts) policy costs, risk of failure etc	On-model inclusion of non-technical factors (e.g. air quality examples in UKTM/ESME) Off-model (multi-criteria) characterisation of scenarios beyond system costs, quantitative (e.g. QUALYs, welfare adjustment) and qualitative

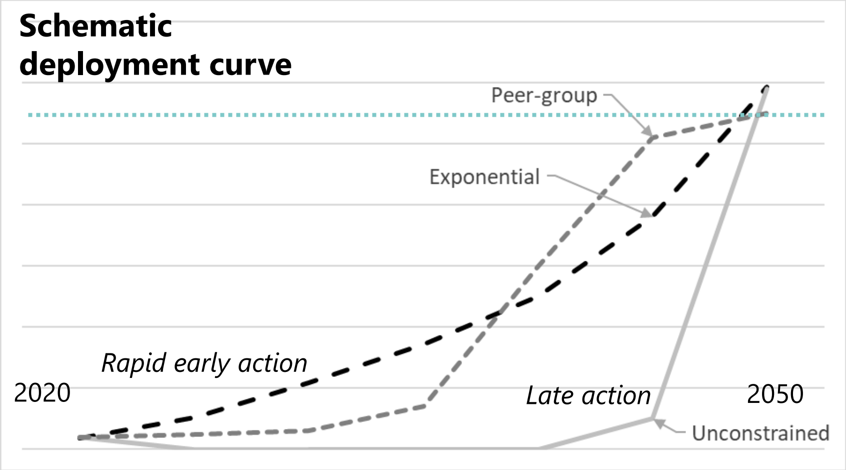
* Attempts to resolve these limitations are addressed in a subsequent section of this report

Other challenges of including greater consideration of societal change within pathway design

- Concern raised among both internal and external interviewees that the use of techno-economic models has potential to promote particular solutions that are more challenging to realise in reality than recognised in models. Pathways need to be socially acceptable and policy routes to deliver outcomes need to be plausible
- It was noted that some of the preferred long-term Net Zero sectoral solutions of techno-economic models have demonstrated little progress within society thus far. This suggests that real-world hurdles are potentially not being incorporated into models or are assumed to be overcome in the future, and that some barriers to engagement are not yet addressed by policy or industry
- From a practical point of view, policy analysis (although not necessarily policy design) is more straightforward when behaviour change does not need to be considered – although at a sector-level behavioural change has been implemented in analysis, this is sensitive to assumptions (e.g. preferences, derived from survey data) which may themselves change as social norms evolve
- Potential robustness of "societal data" evidence versus technical data. Social/behavioural data is typically sourced from surveys & pilots (challenging and costly to collect), proxy information and, sometimes, natural experiments or observations; it's often limited in energy system or consumer scope. Need to disaggregate, affecting robustness
- How and when to engage policy teams and social scientists and to integrate own insights. Some indications of users of Net Zero modelling being distanced from pathway design fundamentals – evolving analytical best-practices may be valuable
- Measurement of utility/welfare in long-term pathways is challenging. Suggestions that Green Book incentivises narrower project analysis and disincentivise cross-cutting projects, which may disproportionately affect behaviourally focused projects
- Feedbacks and willingness to pay clearly missing points from WESMs. Some of these missing points are due to integration challenges with the incumbent models, whereas others are difficult to implement more generally

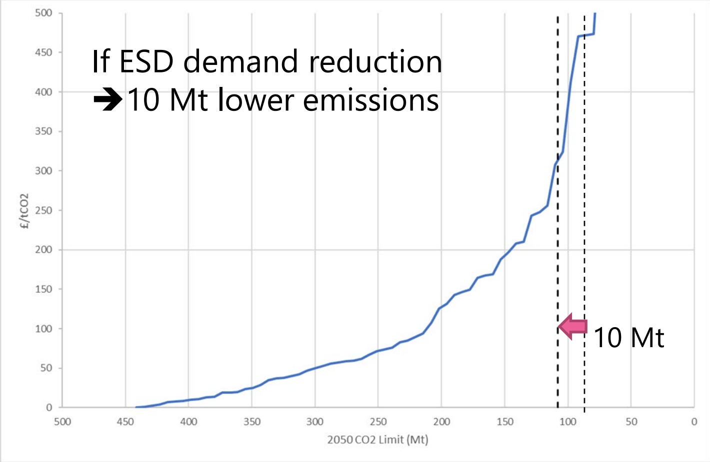
Illustrative examples*: technology deployment and ESD reduction

Example 1: Technology deployment characteristics



- Typical outcome of normative, optimisation-based WESMs: smooth (exponential) or "bang-bang" (unconstrained) response. More realistic uptake curves may differ from standard options
- WESMs include simplification of costs and preferences: in particular learning effects are not included directly (cost/performance assumed to improve)
- In reality potential for early barriers to take-up, peer-group impact and perhaps some challenging segments to reach and represent in models

Example 2: (exogenous) ESD reduction



- For ESDs such as aviation where reduction leads to a direct reduction of emissions, result is effectively a **relaxing of the GHG target for the rest of the economy**
- For WESMs with exogenous ESDs this action is superficially cost-free, although typically is considered to impact welfare. Alternative of using endogenous ESDs is discussed elsewhere
- Towards Net Zero the MACC is at its steepest thus the impact on **techno-economic** transition cost can be sizeable

* Examples taken from pathways modelled using ESME and are offered as illustration only

Benefits of addressing shortcomings

- Provides a more realistic reflection of societal change in short and long-term analysis, providing evidence for (and potentially tempering) "normative optimism" within the typical techno-economically derived pathways. Ensures adequately represented behaviour is included within the process of using WESMs and other tools
- Easier, clearer, tailored and more impactful policymaking – for example, less effort is likely to be needed to convert a "system optimisation" into appropriate, actionable policy as applied in the real world. Avoidance of modelled pathways where no plausible policy is envisioned to help deliver outcomes (leading to iterative revision of pathways)
- Some specific interventions (e.g. energy efficiency) are difficult to consider robustly within behaviourally-limited models and, where they are, feedback mechanisms are often neglected. Addressing these allows the impacts to be more credibly assessed
- Provides a more transparent picture of existing assumptions (such as baked-in behaviour change) to a range of HMG stakeholders, ensuring clearer quality assurance and peer-review critique of analysis across the whole analytical chain
- Informs future data collection and usage principles, in particular data about societal change based on the needs of modellers and policymakers
- Raises awareness of need for greater consideration of behavioural change within the full scenario design process (including modelling principles) and potentially ensures a greater level of internal consistency between assumptions
- Offers the potential for better explication and treatment of uncertainties within pathways (and thus impact of policy)
- Motivating cross-disciplinary working both within HMG and elsewhere

Intervening to deliver these benefits involves adaptations to models or to modelling practices and analysis outside and alongside models

Potential methodological improvements

WP3 has explored potential methodological improvements to existing modelling tools and process

I1. **Inclusion of behaviour endogenously in existing HMG tools**: adapting key models to incorporate elements of society and behaviour within model decision making

I2. **Iterative linking with more detailed tools**: soft- or hard-linking into sector or sub-sector-level tools that include greater sophistication around decision-making

I3. **Methods applied alongside models**: management of societal/behavioural elements off-model, alongside careful development of scenarios and appropriate expert participation

I4. **Narrative and discussion**: collecting and presenting information about scenarios (potentially radically different in terms of the role and norms within society)

Methods of endogenising behaviour in existing WESMs [I1]

Method	Implementation challenge	Implementation examples
Own-price elasticity of demands: characterising sensitivity of modelled demand to changes in service price	Uncertain elasticity values & interpretation – macroeconomic calculations Some complexity of implementation in WESMs Adjustment of model ethos from system cost to welfare	TIAM [5], ESME [6], MARKAL-MED [7], BLUE [2]
Cross-price elasticity: characterising sensitivity of demand to changes in (price of) other demands	Similar to price elasticity	TIAM [8]
Technology/energy actor-specific discount rates: characterising sensitivity to investment versus ongoing costs	Based on limited, uncertain empirical evidence Potentially requires model disaggregation (technology and purchaser)	TIAM [5], BLUE [2] Included to a degree in UKTM
Intangible costs: characterising perceived non-financial impacts of deploying technologies	Choice from large number of relevant intangible costs Uncertain evidence base for costs	BLUE [2]
Behavioural constraints: characterising other behavioural elements that affect technology choice, including feedback mechanisms	Complexity of some plausible constraints (e.g. nonlinearity) Choices may excessively restrict deployment	NTM [9], TIMES [10], CVEI [11], MUSE [12]
Endogenous technology learning: characterising technology learning-by-doing and feedback	Uncertainty of learning rates Challenge/performance issue of representing non-linear trend in linear WESMs Marginal costs (e.g. CO_2 price) less straightforward to obtain	TIAM [13], MARKAL [14]
Exponential uptake constraints: characterising the uptake/diffusion characteristics for emerging technologies & supply chains	Limited types of uptake growth easily applicable to WESMs Sensitivity of uptake to form of constraint Engineering/supply-chain focused with limited societal insight	Included in UKTM and ESME
Energy user segmentation: disaggregating consumer types to allow more tailored decisions to be made	Increased model complexity & performance impact Needs to be combined with other elements such as actor-specific hurdle rates	TIMES [10], MUSE [12], MESSAGE [15] Included to a degree in UKTM and ESME
Actor myopia or imperfect information: considering short rather than long-term decision making	Requires significant model reformulation No correction for preferences	MESSAGE [16]
Modal switching: structuring ESDs such that greater levels of actor behaviour change are permitted	Challenging to ascribe costs & apply constraints to some mode switches Whole system costs may not drive modal switch	TIMES [17], ESME [18], BLUE [2]

Endogenising behaviour: further commentary [I1]

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Demand elasticity

- Own-price demand elasticity has been tested within WESMs e.g. in UKTM, TIAM-Grantham, TIAM-UCL and ESME [5-7]. From discussions with HMG, it is our understanding that this is not currently implemented within UKTM as used in BEIS but is available within the TIMES framework
- Demand elasticity is seen as a useful analytical tool by experts but effects can be stark and require careful consideration. Traditionally this has highlighted value for demand reduction in some sectors (transport most prominently) – value is as an exploratory tool rather than within scenario design directly
- Challenges in derivation of elasticity factors from recent macroeconomics & uncertainty [19]; also applicability to long-term structural demand changes rather than marginal adjustments. Difficult to apply to areas such as dietary change where not traditionally monetized within WESMs, which focus on the energy sector

Uptake and intangibles

- Outcome-focused approach for technology uptake is typical – rates bounded by engineering constraints and reflect need to achieve certain future design rather than modelling societal response. Alternative tools (e.g. ABMs, system dynamics models) may be well-placed to deliver uptake profiles based on more sophisticated decision-making concepts
- Monetising "non-market" costs (intangible costs, disutility costs or frictional costs) or employing related constraints is not universally done. A form of disutility cost associated with air pollution damage has been tested in UKTM [20] and ESME [21], but *energy-related* intangible costs are included in fewer example studies, e.g. using the MESSAGE [15] and BLUE [2] models. Non-market constraints such as travel time or fixed choices have also been incorporated into UKTM [10] and ESME [18]
- Related is the choice of hurdle rates to employ in models, reflecting risks consumers perceive and sensitivity to making (sizeable) energy investments, and are intimately linked to policy environment. WESMs typically use a simplified view of investor hurdle rates, ranging from no variation (ESME) to mixed hurdle rates (UKTM). These have the ability to influence actor behaviour via investment preference, although this is likely to be most compelling within a modelling framework having a socio-economic or Rogers-like population disaggregation – not currently employed extensively within UKTM

Decision making and optimisation

- A final point is around the decision making process within the relevant models. The existing optimisation-based WESMs can be interpreted as being based on a hypothetical designer building out a system consistent with GHG targets, with perfect foresight of future technological and demand evolutions. The existing mature WESMs thus cannot easily be adjusted to shift the perspective to other actors and to incorporate feedback mechanisms. One option is to apply shorter-term planning ("myopia"), as has been explored within TIMES [16], but alternative models (e.g. ABMs) may be better placed to provide this insight
- Deployment of agent/actor-based models to a whole energy system modelling context is an emergent field with few example models being prominent (MUSE, BLUE, TEMPEST [22]). Multiple interviewees indicated that BEIS is engaging with ABM experts to explore the further potential in this area

Example from transport sector: monetising behavioural features relating to choice [I1]

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In the referenced material, social (survey) data combined with bottom-up estimates to form intangible (“disutility”) costs

Disutility cost sub-component	Description of attribute	Monetisation approach
Range anxiety	Monetises perceived anxiety felt by consumer when depending on limited-range, all-electric vehicle for all daily driving needs. Relevant for all-electric vehicles only.	Proxied based on amount consumer willing to spend on rental cars over a year to satisfy driving needs on days when all-electric range is insufficient. Costs depend on charge-sustaining capacities of vehicles (driving ranges), vehicle efficiencies, driving distances, the availability of recharging stations, and the attitudes of consumers toward technology risk.
Refuelling station availability	Monetises perceived inconvenience/hassle felt by a consumer when assessing ease of access to refuelling stations. Only relevant for liquid/gas fuelled vehicles	Proxied based on estimated time needed for refuelling events to reach fuel station. Aggregating time demands & converting them into monetary values (according to studies, consumers put more value on time associated with refuelling) results in disutility cost. Costs depend on vehicle ranges/efficiencies, driving distances and availability of refuelling stations within network.
Risk premium	Monetises willingness of consumer to adopt or avoid new technologies. Measure of perceived technology risk to the consumer; hence, relates to all alternative fuel vehicle technologies	Costs depend on stock of particular vehicle type within given region, as this affects consumer’s perception of technology’s novelty or unfamiliarity at any point in time. Costs differentiated by adopter groups when respective vehicle stock is nil; they approach zero as the stock grows, following an exponential function.
Model availability	Monetises propensity of consumer to avoid new technologies because desired vehicle available in limited number of makes/models (by different automakers, for different vehicle platforms)	Costs depend on sales of particular vehicle type within a region at given point in time, as this affects diversity of vehicle models on offer. Cost premium when sales of the respective vehicle type are nil (i.e., when the models on offer are limited); they approach zero as sales grow (and numerous models become available), following a logarithmic function.
EV charger	Unit cost of installing charger for a single EV. Only relevant for all-electric vehicles and PHEV.	Full cost of installing dedicated charger at home/work or partial cost of shared public fast-charger within transport network (where costs divided up between the vehicles that use them).

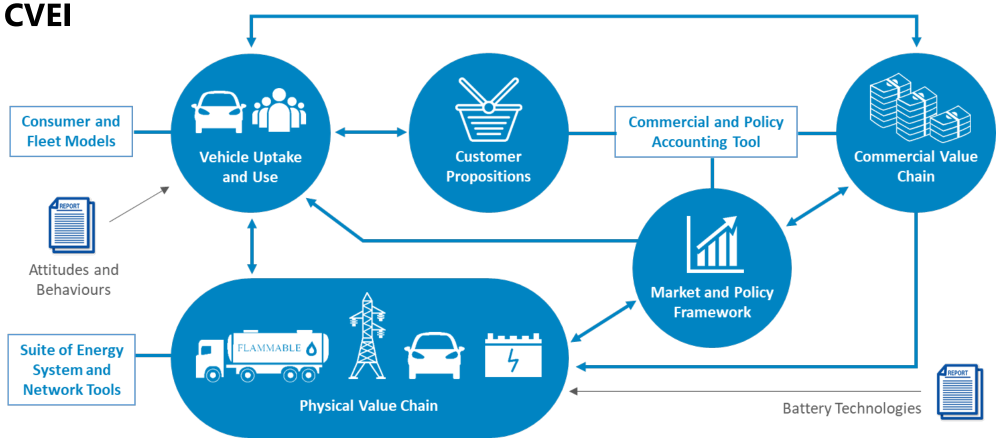
Adapted from McCollum *et al*, “Improving the Behavioral Realism of Global Integrated Assessment Models: An Application to Consumers’ Vehicle Choices”, *Transportation Research Part D: Transport and Environment,* (2016) [15]

Linking methods [I2]

- Modular linking: hard- or soft-linking of more detailed tools into or within the WESMs to find a solution that is consistent across several levels of detail
- Some holistic models already take this approach:
  - CVEI (Energy Systems Catapult): the transport-focused CVEI model iterates on uptake and whole system, finding a pathway that satisfies UK-wide targets but also includes uptake attitudes [11]
  - MUSE (Imperial College): market clearing algorithm replaces optimiser, with ABMs driving sector-level decision. Iteration until agreement of prices across agents [12]
  - WESM + CGE (e.g. University of Strathclyde): groups have combined MARKAL/TIMES with a macroeconomic model (e.g. UK-ENVI) to assess wider impacts on consumers of following particular decarbonisation pathways [23]
- Several other examples within literature, predominantly considering transport [24] and other sectors such as electricity [25]
- High level of technical complexity within many such solutions

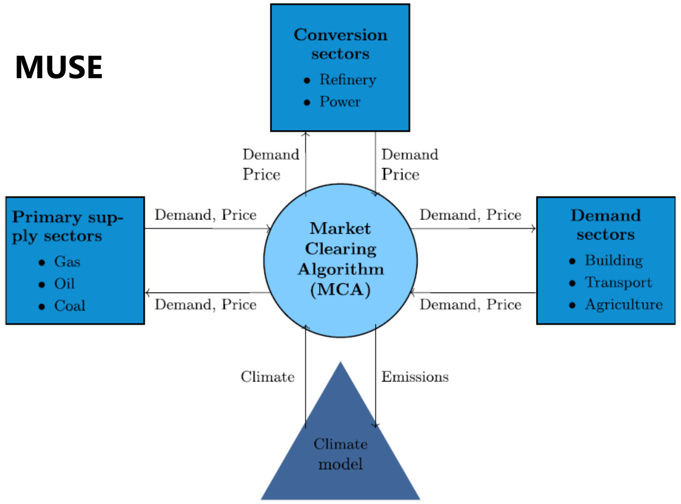
Examples are fully-integrated suites of tools. However, this is not necessary – either a pure soft-link of sector tools without a central WESM or decision algorithm is possible, or ultra-soft linking as part of an input and output validation and off-model adjustment process (as interviewees have indicated is carried out within BEIS)

CVEI



Flow diagram adapted from Ref [11]

MUSE



Reproduced from Ref [12], Sachs *et al*, "An agent-based model for energy investment decisions in the residential sector", *Energy*, 172, 752-768 (2019)

Exogenous treatment of behaviour in WESMs [I3]

- Assuming **fixed, exogenous ESDs is the standard assumption within many initial modelling studies**. These ESDs are typically derived from Government projections of economic drivers (GDP, population forecasts etc)
- The preference amongst some experts in the modelling community is to maintain this approach and adopt a relatively simple WESM as an evaluation tool for **exogenous ESDs that are carefully considered**. For example, the CREDS project [26] has a detailed sectoral focus where energy sector experts assess the potential for ESD change with the aim to combine these within internally-consistent socio-technical narratives
- More generally, the need for **transparency when estimating exogenous inputs** has been stressed by UKERC [3], with the note that "*norms and behaviours with regard to energy are reflected in the*" ESDs and "*are therefore exogenous and the assumptions on behaviours and norms, such as indoor temperatures, are hidden in the off-model projections of* " ESDs
- Examples in the literature are beginning to address this. For example, [27] adopts a methodology where scenarios are designed based on mixed criteria such as levels of carbon taxation, forced-adoption of efficiency or technological outcomes and also lifestyle/habit changes (including scenarios that significantly reduce non-CO_2 emissions). This example includes some but not extensive ESD assumption transparency. It also compares scenarios only in their system design (particularly regarding GHG removal technologies) and emissions, and does not attempt to quantify financial/economic differences between scenarios
- A relevant option is to develop **socio-technical storylines** and to use WESMs with judiciously-chosen ESDs to test the system that results when "optimising" against these scenarios. This approach has been explored in the literature (e.g. [28]) and is similar to the approach used by Energy Systems Catapult in designing its "demand cases" used in modelling supported by ESME. This approach is superficially similar to that followed by BEIS but with the ability to deviate significantly: considering alternative storylines could suggest significant movement from reference case ESDs
- The counterpoint to participatory development of adapted exogenous ESDs is the **role of welfare adjustment**. Classically, an adjustment to ESDs in WESMs leads to a change in utility/surplus, hence the historic use of elastic demands to assess whether demand adjustments should be implemented alongside or in place of technological changes. However, the hypothesis within recent studies and projects is that **long-term demand reduction is not necessarily associated with a true loss in welfare**, and thus there should be no cost adjustment applied to compensate. With a general focus on the *design* of any pathway to Net Zero rather than the real-world cost to transition, scenarios become tools with which to explore policy design rather than focusing on a single starting points for cost-focused quantitative policy analysis

Comparing scenarios based on different exogenous ESDs [I3]

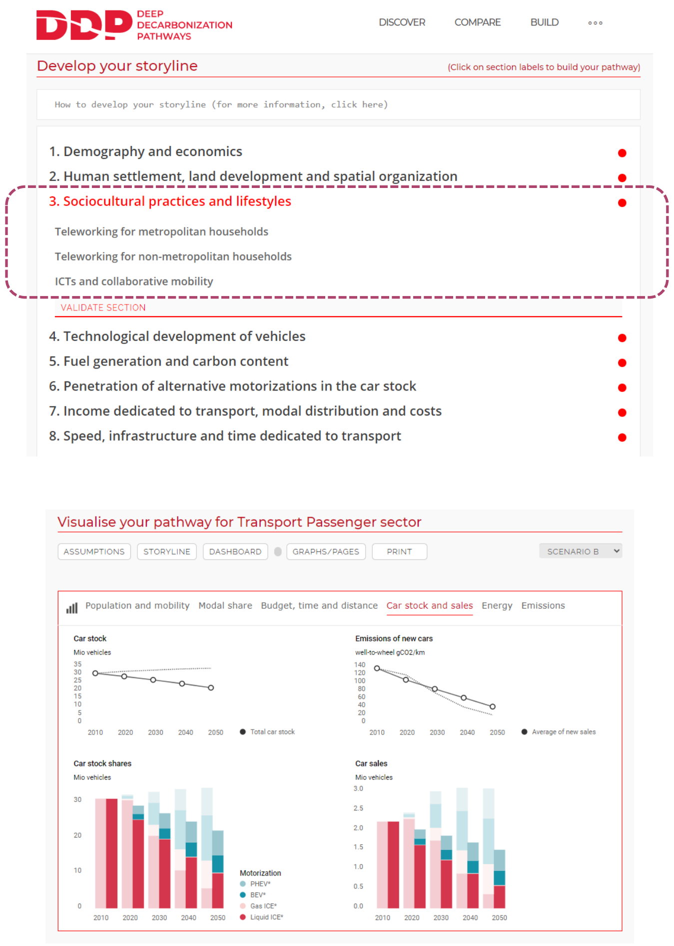
- The conventional focus for assessment energy scenario studies – whether built up using exogenous ESDs or otherwise – tends to be **on chosen system designs and emissions profiles**. This is the case for both the academic literature and also recent Net Zero focused publications by organisations such as National Grid [29] and ESC [30]
- System costs (i.e. the outputs of model runs) are occasionally presented both in **absolute terms and costs relative to a counterfactual**. Within BEIS it is understood that this counterfactual typically represents the continuation of existing policy (which is unlikely to drive decarbonisation success consistent with the Net Zero target), but choice of counterfactual when societal change is anticipated is non-trivial
- There are examples in the literature that present energy system costs for modelling studies with and without adjustments to ESDs and also compare with studies inclusive of endogenous demand elasticity [5] (these studies exclude policy costs and frictional costs/resistance to change) – a direct comparison of system costs is not without precedent
- Typically, however, it is appropriate for analysis of scenarios to be broader than a focus simply on costs. An emerging area of interest is to construct **multi-criteria analysis of scenarios** rather than to simply present standard results of models along with narrative. Multi-criteria methods are well established within HMG [31] as instruments for developing insight about "decision options" (e.g. plausible Net Zero pathways), with the ability to combine quantitative and qualitative (or energy and non-energy co-benefits) features into a single comparison table or metric
- Notable examples in the literature are [32], which carries out MCA analysis of various UK MARKAL scenarios, and [33] which outlines a holistic approach to scenario planning that utilises a specific MCA algorithm to combine criteria into a single score, thus comparing different energy system options in the German federal context. [34] presents specific model outputs such that the most rapid deployment rates are exposed directly, allowing the different scenarios to be assessed immediately. Ref [11] includes MCA as part of a wider suite of analytical activities
- It was the broad consensus of the interviewees, though, that scenario comparisons are not straightforward. An option raised by several interviewees was to explore valuation/monetisation principles akin to those outlined earlier in the context of endogenous treatment of behaviour, such as the "natural capital" valuations explored within Defra. Even if not integrated into WESMs a viable option is to calculate such non-energy elements *alongside* the modelled scenario features. However, the view of the interviewees was that the energy modelling community is in need of some further development in terms of its scenario comparison practices

Emerging examples of transparent participatory methods for ESDs [13,14]

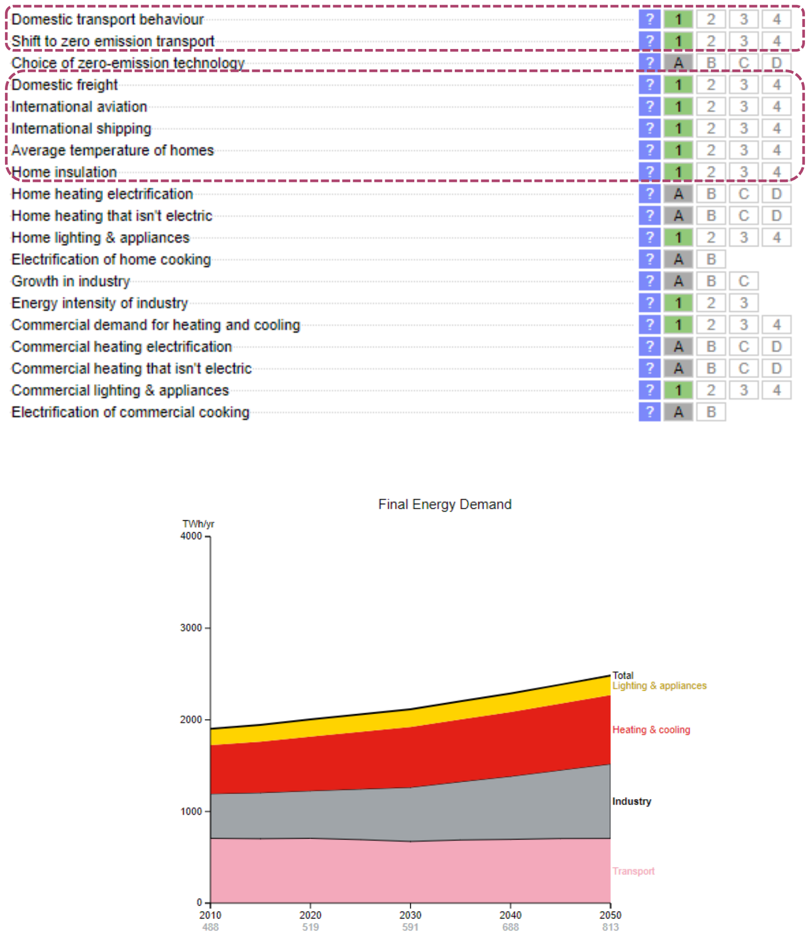
Bottom-up construction of ESDs

Visualisation of scenarios

DDP Initiative [35]



2050 Carbon Calculator [36]



Additional thematic findings from external interviews

- There was general agreement amongst the interviewees that **the role of societal change has been under-represented in prominent scenario studies**, in part because of the challenge of incorporating behaviour within the prominent WESMs. ESD assumptions and forward-looking assumptions are often deeply embedded within scenarios and are not transparent to the reader. The COVID-19 pandemic has highlighted a lack of confidence in some of the existing assumptions around ESDs and the extent to which social norms can change

- **Appropriate use of available modelling tools** was stressed by several participants. Adding increasing sophistication *into* models (e.g. endogenous behaviour) is not always apt but better is an evolution of modelling practice by using different tools at the right time and in the right way. There was some discussion around specific use of the incumbent WESMs and their focus on the supply-side and how best to include this within pathway design

- Having said this, some interviewees were **concerned about the role of mathematical optimisation** within the pathway design process, potentially reflecting challenges that HMG raised. A pathway built on a *central system* optimisation may be difficult to correct for unpalatable distributional effects and may be more difficult for policymakers and policy designers to work with than alternatives

- Social data is increasingly incorporated into quantitative work (e.g. models involving choice), but it was noted that sometimes **the supporting data is problematic for modellers**. Attitudes towards technology and behavioural change are typically inferred from proxies, case studies/surveys or expert elicitation. Survey-based methods are data intensive for adequate coverage for use in models, whereas alternatives are more subjective

- Language and perspectives of modellers and social scientists was raised by some interviewees as a barrier to engagement and critique of pathways. Agreeing on common terminology and an engagement process is likely to be required to improve significantly

- The specific example of **decarbonisation of heat** was raised by several interviewees where the long-term solutions suggested by modelling have not been reflected in recent history, despite some policy interventions. There may be relevant intangibles but the upfront capital cost itself may be the largest barrier. Heat decarbonisation may be associated with a “branching point” and thus multiple pathways with actions needed could be relevant

- **Uncertainty of pathways** was raised by several groups. Academic groups are typically comfortable with incorporating uncertainties into analysis but it was appreciated that there is a need to communicate results to stakeholders in the right way using insightful metrics, not simply costs. Broader economic insights are more challenging to extract from modelling studies

Illustrative options for HMG to consider in WP4

Either could be progressed within WP4

Testing of endogenous methods

- The endogenous methods outlined in this report have all been trialled in the literature but examples are limited thus far in the UK's Net Zero context
- Many of the methods could be tested within existing Net Zero-achieving WESM environments such as ESME and assessed against a wider set of criteria (such as the growth rates illustrated in [34]) along with other criteria to be agreed with HMG
- **Specific priority examples to test in WP4 could be the role of intangible costs and hurdle rates (on and off-model), where the initial WP3 review would be built upon and the pathway sensitivity to these parameters assessed**
- In the longer-term, more sophisticated methods reviewed (involving either disaggregation or change in model methodology) could be further explored amongst the literature or tested. The UKTM user group has experience in developing these functions and may be well placed to take this forward

Energy Service Demand transparency

- The practice of researchers in developing transparent ESDs as a proxy for studying societal change is clear, reflecting approaches used within tools such as the MacKay Carbon Calculator
- Thus ESC's provisional proposal for a Demand Builder tool to help build transparent scenarios that contain potentially radically different societal assumptions remains relevant and deliverable within WP4
- **WP3 research has suggested that the scope of this tool is best adjusted from the initial view, with evolution of social norms affecting not just ESDs but other behavioural characteristics (e.g. rates of technology take-up)**
- A clear benefit of a Demand Builder is as an agnostic integrator of sector-level tools and expertise that may change over time as models and modelling practice evolve
- The WP3 findings have suggested that benefit of a Demand Builder is maximised when combined with dashboards enabling HMG to compare scenarios clearly against multiple criteria. This could also incorporate some of the non-market costs outlined earlier

Deeper exploration of emergent modelling methodologies

- The incumbent WESMs are powerful tools for integrating sector-level insights and ensuring supply/demand balance consistent with long-term aggregate targets. However, they are not designed to be true decision engines for individuals; practice is to utilise pathway information in further analysis
- Some emerging tools in the literature address the decision-making process directly, in essence replacing the optimisation with an "equilibrium" consistent with different needs of stakeholders in the energy system
- These agent/actor-based tools are recent developments within academia and limited application to HMG process is understood to have taken place
- Follow-up with key model and practice developers could be explored as part of a longer-term assessment of the toolchain best exploited within Net Zero system design. At this stage ESC recommends only that HMG consider this option, but a more structured recommendation could be pursued as part of WP4

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