Improving deep decarbonisation modelling capacity for developed and developing country contexts

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Abstract

Energy models are essential for the development of national or regional deep decarbonisation pathways (DDPs), providing the necessary analytical framework to systematically explore the necessary system transitions. However, this is challenging due to the long time horizon, the numerous data requirements, and the need for transparent, credible approaches that can provide insights into complex transitions.

This paper explores how this challenge has been met to date, based on a review of the literature and experiences of practitioners, drawing in particular from the Deep Decarbonization Pathways Project (DDPP), a collaborative effort by 16 national modelling teams. The paper finds that there are a range of modelling approaches that have been used across different country contexts, chosen for different reasons, with recognised strengths and weaknesses. Key motivation for use of a given approach includes being fit-for-purpose, having in-country capacity, and the intertwined goals of transparency, communicability, and policy credibility.

From the review, a conceptual decision framework for DDP analysis is proposed. This three step process incorporates policy priorities, national characteristics, and model agnostic principles driving model choices, considering developed and developing country needs and capabilities, and subject to data and analytical practicalities. Finally, an agenda for further development of modelling approaches is proposed, vital for strengthening capacity. These include a focus on model linking, incorporating behaviour and policy impacts, flexibility to handle distinctive energy systems, incorporating wider environmental constraints, and development of entry levels tools. The latter three are critical areas of development for developing country contexts.

Policy Relevance statement

Following the Paris Agreement, it is essential that modelling approaches are available to enable governments to plan how to decarbonise their economies over the long term. This paper takes stock of current practice, identifies strengths and weaknesses of existing approaches, and proposes how capacity can be strengthened. It also provides some practical guidance on the process of choosing modelling approaches, given national priorities and circumstances. This is particularly relevant as countries revisit their Nationally Determined Contributions, to meet the global objective of remaining well below a 2°C average global temperature increase.

Keywords: Decarbonisation, pathways, modelling, policy, tools

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1. *Introduction*

1.1 The need for deep decarbonisation pathways

According to the IPCC (2014), to ensure a better than even chance of remaining below a 2 °C average surface temperature rise (relative to 19th century global temperatures) global annual CO_2 emissions will need to be reduced by 42-57% by 2050 (relative to 2010), and 73-107% by 2100 to maintain a global carbon budget of 800-1100 $GtCO_2$. To achieve this while ensuring socio-economic development, all countries need to act soon and with robust ambition to avoid dangerous climate change.

As a response to this scientific imperative, the Paris Agreement commits countries to collectively holding the increase in the global average temperature to well below 2°C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5°C (UNFCCC, 2015). As part of the COP21 process, national governments pledged Intended Nationally Determined Contributions (INDCs), voluntary emissions targets in 2025 and 2030. These two ideas, long term deep decarbonisation and nearer term action under INDCs, to be intellectually coherent, require a national development pathway. Such a pathway starts by considering the emissions level necessary in 2050 to meet global climate goals, and assesses the necessary actions that need to happen from today to 2050, thereby providing an assessment benchmark for INDCs. The development of such pathways is the purpose of the Deep Decarbonization Pathways Project (DDPP).[1]

The DDPP is a collaborative initiative that seeks to demonstrate, physically and economically, how countries can transform their energy systems to deliver deep decarbonisation consistent

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[1] The Deep Decarbonization Pathways Project, www.deepdecarbonization.org

with national development priorities.[2] This transition is represented by individual country Deep Decarbonisation Pathways (DDPs). A key strength of the approach is that the country DDPs are prepared by in-country teams with local knowledge independent of government, taking careful account of the national political, economic, technological, and geographic context. The pathways also operationalise the types of action required now and through time out to 2050, using robust, credible and transparent modelling approaches. In doing so, they can also provide a catalyst for a debate amongst stakeholders about the technical pathways and the policies to achieve them. However, it is a non-trivial exercise to develop and implement approaches across all sectors in the economy over the long term in a systematic and defensible way.

1.2 Challenges to developing and applying modelling approaches

There are multiple challenges associated with modelling effective national-scale DDPs. *The long time horizon means significant uncertainty* across many phenomena which have a strong impact on emissions, including population, economic growth, and the evolution of energy supply and end use technologies. Incorporating and communicating this uncertainty in a transparent way is difficult, but its importance and impacts must be recognized and understood by analysts, stakeholders, and decision makers (Lempert, Popper, & Bankes, 2003), (Stirling, 2010).

Modelling approaches need to be transparent, practicable, and represent common exogenous shocks and policies as accurately as possible, while recognizing complex dynamics, including: i) energy system operation; ii) technology stock turnover; iii) technology innovation; iv) firm and household behaviour, v) energy and non-energy capital investment and labour market adjustment dynamics leading to economic restructuring, and vi) infrastructure deployment and urban planning (DeCanio, 2003), (Laitner, DeCanio, Koomey, & Sanstad, 2003), (Hourcade, Jaccard, Bataille, & Ghersi, 2006), (Mundaca, Neij, Worrell, & McNeil, 2010), (Waisman, Guivarch, & Lecocq, 2013), (Pfenninger, Hawkes, & Keirstead, 2014).

Multiple policy priorities often require different types of insight, and may require differing modelling approaches. Decarbonisation will impact sector and national output, require significant equipment and infrastructure investment, change energy system operation, impact different socio-economic groups disproportionately, and may have interactions with other

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[2] Some teams also focussed on necessary policy packages, and some on all (not just energy system) emissions.

social, economic and environmental priorities. All these issues may potentially be assessed most effectively by distinct models (Strachan, Foxon, & Fujino, 2008).

Emission reduction options are only as real as policy to implement them; actions and policy must be considered in tandem. Good modelling tools allow, suggest and provide the capability of analysing a range of plausible policies without predetermining them (Bataille, Jaccard, Nyboer, & Rivers, 2006).

Given the challenge, modelling tools are fundamental to the ability to develop DDPs. The many quantitative assumptions for a DDP need to be organized and communicated in a coherent and consistent way, and this can be done via a number of modelling frameworks, all with strengths and weaknesses, and appropriate depending on purpose and context.

1.3 The need for adequate modelling approaches

Given the requirements of DDPs, it is important to understand the relative merits of different modelling approaches, and to consider whether they are fit for purpose, and where further development is required. Energy system modelling tools are being increasingly applied to environmental sustainability issues. However, the motivation for their development, and the radical changes envisaged in a future under DDPs, raises questions about their applicability, and the need for a new set of tools to meet the emerging challenges.

The original motivation for many energy specific models was a focus on energy security, emerging from the oil crisis of the 1970s, and the need for planning vertically integrated, natural monopoly electricity systems (Rath-Nagel & Voss, 1981), (Laitner et al., 2003). Models were developed with fossil-based systems in mind, and were OECD-focused. Expanding DDP analysis capacity means that approaches need to be capable of exploring radically different systems with a low fossil, high renewable resource base. They must also reflect the situational needs of non-OECD countries (Pandey, 2002), (Urban, Benders, & Moll, 2007). Some key limitations with existing energy systems modelling tools and necessary methodological improvements are identified later in this paper.

1.4 Objectives and structure of the paper

This paper aims to propose a process toolkit for developing, extending and supporting DDP activities internationally. In this context, a toolkit is the analytical framework for thinking about DDPs, starting with policy priorities and then moving on to guidance on model choice, application, and practical challenges. Therefore, it concerns how modelling tools are applied to different questions. To do this, we first identify the different approaches that have been already been adopted for undertaking DDPs, understanding the motivation for their use, and their relative strengths and weaknesses. This is done via a literature review (section 2) and a survey of DDPP teams (section 3). Section 4 develops a more encompassing process-based approach to developing a DDP based on policy priorities, system characteristics and practical considerations. Guidance is also developed for extending DDP capacity via entry level tools, while recommendations set out the methodological improvements for existing approaches to enhance their application for DDPs. Section 5 concludes.

2. Literature review of approaches to deep decarbonisation

The DDPP initiative builds on the experiences of practitioners worldwide analysing increasingly ambitious levels of national emissions reduction (in effect, DDPs). To focus the literature review, a set of criteria were first established, based on the principles of the DDPP. Analyses were: 1) national or sub-national scale to adequately represent country specifics (i.e. not global), 2) undertaken by national modelling teams with local knowledge, 3) economy wide with sectoral disaggregation, including energy supply and demand balance, 4) accounting for combustion emissions at a minimum (although eventually DDPs should consider all emission sources), 5) adopting a time horizon extending beyond 2030, ideally to 2050, 6) assessing emission reductions of at least 50% by 2050, relative to 1990/2010, 7) assessment of investment and more general economic impacts, and 8) providing explicit representation of the emission reduction drivers (e.g. regulations, carbon price, annual or cumulative emissions cap). These criteria ensure that we reflected the key principles of DDPs: policy orientated, a strong level of ambition in the longer term, capture of the main emission sources, and crucially, nationally appropriate analyses. Finally, we have focussed almost solely on academic peer reviewed literature.

Table 1 summarizes some of the key decarbonisation analyses undertaken to date.

Table 1. Review of national deep decarbonisation analyses

Country	Study reference	Modelling approach	Models
Canada / China	(Bataille, Tu, & Jaccard, 2008)	Hybrid: Economy wide B-U firm and household behaviourally realistic simulation, equilibrium of energy supply and demand, elastic end use demands	CIMS Canada and China
China	(Chen, Wu, He, Gao, & Xu, 2007)	B-U optimisation (w/ hybrid macro extension)	MARKAL (w/ MACRO / ED extensions)
China	(Kejun, Qiang, Xing, & Xiulian, 2010)	Mixed framework: BU technology model linked to CGE and global emission models	Integrated Policy Assessment Model China (IPAC)
France	(Mathy, Fink, & Bibas, 2015)	Hybrid CGE, dynamic updating of production functions using POLES B-U model.	IMACLIM-R
France	(ADEME, 2012)	Hybrid multisector CGE with some bottom-up (B-U) attributes for household energy consumption	Three-ME
Germany	(Schmid & Knopf, 2012)	Hybrid CGE, integrating detailed energy system	REMIND-D
India	(Shukla, Dhar, & Mahapatra, 2008)	Mixed framework; B-U optimisation, CGE, accounting model	MARKAL/ AIM-CGE/Snapshot accounting model
India	(Shukla & Chaturvedi, 2012)	IAM, and CGE framework	GCAM-IIAM
Ireland	(Chiodi et al., 2013); (Deane et al., 2013)	B-U optimisation	TIMES
Japan	(Fujino et al., 2008)	Mixed framework: Population & household models, BU models for buildings & transport, CGE	Pop. and Household (PHM); Building (BDM); Transportation (TDM); CGE
South Africa	(Winkler, 2007)	B-U optimisation, CGE	LTMS model
Switz.	(Babonneau, Thalmann, & Vielle, 2015)	CGE, Switzerland is an individual model within a global matrix of models	GEMINI
UK	(Strachan, Pye, & Kannan, 2009)	B-U optimisation, with simple CGE extension	MARKAL-MACRO
UK	(Usher & Strachan, 2012)	B-U optimisation, incorporating stochastic programming	MARKAL-Stochastic
UK	(Ekins et al., 2013)	B-U optimisation	MARKAL (various extensions)
UK	(Pye, Sabio, & Strachan, 2015)	B-U optimisation, using probabilistic framework	ESME
USA	(Williams et al., 2012)	Accounting model	PATHWAY
USA	(McCollum, Yang, Yeh, & Ogden, 2012)	B-U optimisation (TIMES)	CA-TIMES
USA	(Paltsev, Reilly, Jacoby, & Morris, 2009)	Dynamic recursive CGE	MIT-EPPA
USA	(Ross, Fawcett, & Clapp, 2009)	Regional CGE	ADAGE
USA	(Tuladhar, Yuan, Bernstein, Montgomery, & Smith, 2009)	Top-down (T-D) dynamic CGE combined with BU electricity sector.	MRN and NEEM
USA	(Goettle & Fawcett, 2009)	Econometrically estimated dynamic CGE, external MACs for “exotic” technologies	Inter-temporal General Equilibrium Model (IGEM)

In terms of **regional representation**, there is substantial UK and US presence. The UK presence is due to its legislated 80% reduction target in 2050. The US presence is because of EMF 22, where several US modelling teams analysed 50% and 80% reductions from 1990 by 2050 as per Congressional priorities of the time. There are three Chinese studies due to its importance for global emissions, and two studies for India, both from the perspective of decarbonisation combined with development.

Figure 1 arranges the models used by **fundamental type**. We have organised the models by abstraction and complexity of system dynamics, with accounting models being the simplest (in abstraction if not sector and technology complexity), and top-down and integrated assessment models being the most abstract. Abstraction has been chosen as the dimension of comparison because it helps clarify the trade-off between dynamic complexity versus clarity and communicability, with accounting models having the least dynamics but being the easiest to explain to stakeholders and policymakers.

Figure 1. Model types from literature review

Accounting	Bottom-up (B-U)	B-U based hybrid	Mixed linked B-U+T-D	Top-down (T-D) based hybrid	National IAM
PATHWAY (US)	MARKAL-TIMES (UK) CA-TIMES (Cal) MARKAL Stochastic (UK) MARKAL (UK) ESME (UK) LTMS (SA)	CIMS (CAN-CHIN) MARKAL-ED (UK) MARKAL-MACRO (UK) MARKAL-ED (CHIN) MARKAL-MACRO (CHIN)	Pop, Buildings, Trans, CGE (JP) MARKAL-AIM-Snapshot (IN) IPAC (BU-CGE) (CHI)	IMACLIM-R (FR) MIT-EPPA (US) MRN-NEEM (US) ADAGE (US) THREE-ME (FR) REMIND-D (GER) GEMINI (Swiss)	GCAM-IIM (IN)

Accounting models like PATHWAY disaggregate all the major energy using and supplying sectors in a given region and balance energy supply and demand, but they are deliberately relatively simple in investment and behavioural dynamics, if not sectoral and technological detail, to allow for scenario analysis that is approachable by stakeholders. Their dynamic simplicity underpins a key strength – a relatively less steep learning curve than other modelling systems in this analysis. Their clearest weakness is that they have no theoretical or practical underpinning by which to forecast the effect of policy shocks on the economy or energy system in general.

Accounting frameworks are the most transparent and easiest to use. They also seem to be the main method for assessing non-energy emissions (e.g. LULUCF as a linked model to other modelling approaches). Their use is, however, limited for assessing the impact of market based policies, e.g. performance mechanisms, cap and trade, and carbon taxes, not just for the direct impacts on emissions but follow-on effects of financial recycling methods. If, however, data collection is well organized and evolution to more sophisticated modelling is planned, they are good entry level tools to bottom-up (B-U) and B-U hybrid models, which allow policy, costing and some investment analysis.

Bottom-up models, of which the MARKAL-TIMES family is most widely used and ESME being another example, ((Chiodi et al., 2013), (Deane et al., 2013), (Usher & Strachan, 2012), (Ekins et al., 2013), (Pye et al., 2015)) are focussed on the energy system technology stock and how it can change through time. They have very detailed, often economy wide, linked maps of energy use from supply through end use demand, and their operating paradigm is minimization of life cycle costs for specific intermediate and end use energy demands through technology competitions, often in response to capital, labour, energy and emissions price changes.

Their strengths include an integrated full system representation and explicit recognition of capital, operating and fuel costs which provides a basis for least cost analysis, normally based on a financial discount rate. Because of their technical depth and capacity for modelling capital stock turnover, they can also model the effects of technology regulations, a common requirement of decision makers and typically a weakness of top-down models (see later discussion). Their weaknesses are their data intensiveness, behavioural simplicity (cost minimization based on financial discount rates does not completely describe firm and household behaviour), exogenous demands for energy services, lack of capacity to model the financial recycling effects of emissions charges, and inability to model economic structural change. As a practical consideration bottom up models (and all models that follow) typically have steep learning curves.

Bottom-up based hybrids such MARKAL Elastic Demand (ED) (e.g. (Ekins et al., 2013), (Chen et al., 2007)) and MARKAL-MACRO (Strachan et al., 2009) attempt to include key top-down dynamics (e.g. behavioural realism through demand adjustment in the face of policy changes as well as the use of maximization of producer and consumer's surplus in the case of ED and MACRO variants of MARKAL-TIMES) in what is otherwise a bottom-up framework. CIMS[3], which also incorporates elastic demands, while sharing many of the design characteristics of MARKAL, directly tries to include elements of top-down firm and consumer

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[3] Used for Bataille et al 2008 in our literature review. See (Nyboer, 1997) for a seminal review of the literature. (M Jaccard, 2009), (Mau, Eyzaguirre, Jaccard, Collins-Dodd, & Tiedemann, 2008), (Bataille et al., 2006), (Rivers & Jaccard, 2005), (Horne, Jaccard, & Tiedemann, 2005), and (Mark Jaccard, Nyboer, Bataille, & Sadownik, 2003) further describe this literature and how it was used to redesign an optimization model to simulate revealed firm and household behaviour to make it more policy useful.

behavioural realism directly in investment, operation, and consumption behaviour (e.g. through agent heterogeneity and discount rates and intangible costs established using revealed choice surveys and analysis), especially as it relates to energy using technology choices. It can therefore be described as a simulation as opposed to optimization model. All the bottom-up hybrids share the challenges of having a limited depiction of non-energy system structural change; given a strong policy, while they can capture some economic restructuring, they simply cannot capture the full economy wide pricing, trade and economic structure effects.

Mixed soft-linked and hard-linked models, (e.g. (Fujino et al., 2008); (Kejun et al., 2010); (Shukla et al., 2008)), instead of trying to directly incorporate bottom-up (B-U) and top-down (T-D) attributes, link established B-U and T-D frameworks. These frameworks typically have the advantage of using existing models, typically "soft-linked" (i.e. there is no direct coded connection, but parameters are passed back and forth). These frameworks, not having been designed together, will typically be challenged with boundary issues, i.e. overlapping coverage of systems and their dynamics. Hard-linked B-U and T-D models, and hard-linked systems also incorporating air quality, health, land use and water models, are a frontier that is being increasingly explored and is discussed later in this paper.

Top-down based hybrids are typically computable general equilibrium (CGE) full economy frameworks adapted for energy policy analysis. CGE models operate by maximizing household welfare subject to several operational constraints, including benchmarking of a starting equilibrium, zero windfall profits and all markets clearing. There are many different types, including static models (they are shocked from one future equilibrium to another), dynamic models (which endogenously incorporate savings and investment effects over time) and dynamic recursive models (which simulate investment over time as a series of static models which pass savings for investment to each successive period). Because of the need to describe technological change in DDPs, dynamic and especially dynamic recursive models e.g. MIT-EPPA (Paltsev et al., 2009) are more common.

Top-down hybrids used for energy analysis are distinct from typical CGE models in that they have a recognized need for technological explicitness to represent fundamental changes, especially in the electricity system. Bulk electricity can be made from coal, natural gas, oil, hydropower, wind, solar, biomass, or nuclear, and all these technologies have fundamentally different fuel, emissions, capital, operating cost and labour requirements, and the standard top down CGE techniques, such as constant elasticity of transformation production functions which assume continuous substitution between inputs (e.g. hydropower plants do not blend seamlessly into coal or nuclear plants), have to be modified appropriately, either by modification of the production function structure e.g. MIT-EPPA (Paltsev et al., 2009), or linkage to a specialized electricity model e.g. MRN-NEEM (Tuladhar et al., 2009). Deep decarbonisation will require transformative change in almost all energy using sectors, making technological explicitness mandatory in all sectors.

Top-down hybrids have one key advantage over bottom-up hybrids, in their capacity to model the full impacts on GDP, employment and economy structural change by climate policies, and especially the capacity to accurately simulate the recycling method for carbon pricing, which has a large final effect on policy emissions and economic impact (DeCanio, 2003), (Rivers, 2010). Their key weakness is their inability to accurately model detailed technology regulations, which can be imperfectly ameliorated by more sophisticated production function nesting.

National Integrated Assessment models (IAMS) are full economy models that also include atmospheric GHG and energy balancing components to allow for temperature change targets, and in some cases include damage functions. This means they are necessarily global, and national circumstances are often simplified to the point where they are not useful for national policy debates. The one exception we found specifically represented India’s national circumstances in greater detail. IAMS are also specialized, labour intensive frameworks run by global analysis groups, and would typically be difficult to use successfully by national groups wanting to inform their national debates, due to their complexity and lack of national granularity.

3. Experiences from the DDPP initiative

The literature review in section 2 is complemented by a survey of practitioners in the DDPP initiative, to further understand methodological approaches employed (models used and their application), why such approaches were used, and the challenges of developing DDPs. A survey was developed, and sent to all 16 teams involved in the initiative; 12 teams responded and provided information on: i) type of model used, ii) motivation for choosing modelling approach, iii) limitations of approach, and how these should be addressed, and iv) necessary improvements to modelling approaches.

3.1 *Types of model used*

The types of models used across all DDPP teams are provided in Figure 2, including non-respondents to the survey. Model tools have been arranged according to the categorisation provided in Figure 1, to put the survey in context of the literature review. We observe a strong role for energy system optimisation models, but also other bottom-up frameworks that provide technology-explicit pathways over the longer term. Over half of the teams also use CGE frameworks, either in combination or exclusively, to explore wider economic impacts, reflecting the importance, particularly for policy, of assessing how DDPs will impact on the broader economy. Of the teams exclusively using CGE models, these are of a hybrid nature, with a more explicit representation of the energy system than seen in most CGE models. While many of the research teams have been developing and using national-scale models for many years, there are others where capacity in this field is lower, highlighting the need for a simpler and more robust entry level calculation tool.

Figure 2. DDPP model types [4]

Accounting	Bottom Up	BU based hybrid	Mixed linked BU+TD	Top Down based hybrid	National IAM
US	UK	Canada	Australia	France	None
Indonesia	Russia		Japan	Brazil	
South Korea			Italy	Canada	
Mexico			China		
			South Africa		
			India		

3.2 *Motivation for choice of approach*

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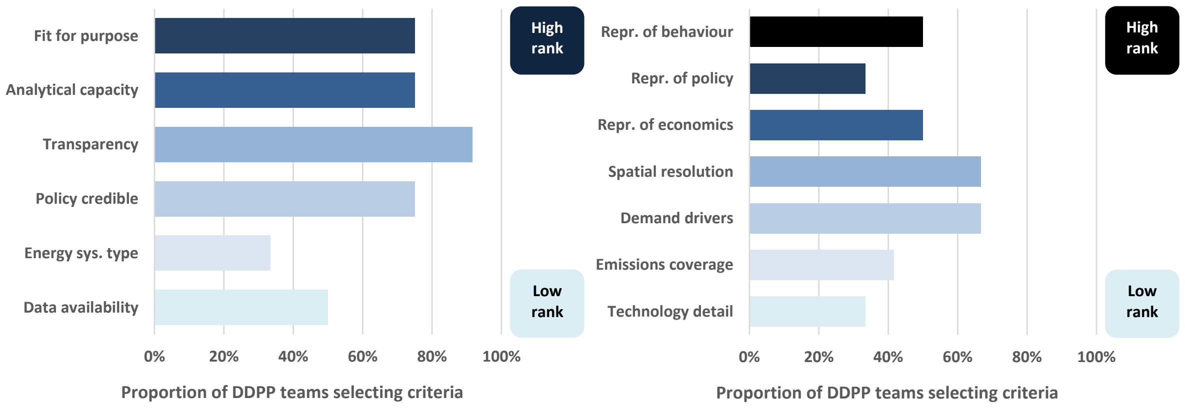
[4] A full description of the modelling approaches can be found in the country reports on the DDPP website, www.deepdecarbonization.org. For each country team, we provide the name of the lead institution / model name: Australia – ClimateWorks Australia & Australia National University/MMRF; Brazil - COPPE/UFRJ/Imaclim-BR; Canada - Carbon Management Canada/CIMS; China – Tsinghua University/SACC; France – EDDEN-UPMF/Imaclim-R; India - Indian Institute of Management Ahmedabad/SLIM (AIM/MARKAL); Indonesia - Institut Teknologi Bandung/DDPP tool; Italy - ENEA/TIMES-GDyn-E-ICES; Japan – NIES/AIM; Mexico - INECC/DDPP tool; Russia - RANEPA; South Africa – University of Cape Town (ERC)/SATIM; South Korea - KDI School of Public Policy and Management/ DDPP tool; UK – University College London/UKTM; USA – E3/PATHWAY. The German analysis was led by the Wuppertal Institute, based on a review of existing scenario analyses.

The types of models used reflect a range of motivations, based on in-country modelling capacity, analysis priorities and a range of other factors. The survey question was *'What matters in terms of choice of models?'* Based on an average ranking,[5] the highest ranked reason was that the analysis approach was fit for purpose (Figure 3). Under this criteria, a number of respondents using B-U modelling approaches highlighted the explicit characterisation of technological options. A number of teams noted the ability of the CGE frameworks to analyse the broader economic impact of climate policies (GDP, employment, economic structure) and consumer response.

A critical factor, ranked second, is the capacity required to use a given approach, with almost all teams selecting this. Either the research team had selected a modelling approach based on their institute's recognised capacity, or had opted for the more simple accounting framework offered by the DDPP due to lack of capacity. Two other criteria also scored highly – transparency and credibility of approaches undertaken. On transparency, this was highlighted in particular by Mexico and the UK as crucial to the use of modelling to inform decision makers. On credibility, Australia, India and the UK highlighted the long track record of using B-U optimisation modelling, and / or previous assessments using similar frameworks. Data availability was lowest ranked, with few teams expressing issues.

Figure 3. Ranking and frequency of criteria selected for motivation of model choice (left) and limitations of approach (right)



3.3 *Limitations of approach*

A further question concerned limitations associated with selected approaches (Figure 3). Limited behavioural representation ranks as the most important criteria in the survey, reflecting a recognised deficit in some of the bottom-up models, particularly those with optimisation

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[5] Selected criteria was ranked equal for those 4 teams which did not explicitly provide a ranking.

frameworks where consideration of behaviour is limited to cost-optimal purchasing and response to price changes.

The explicit representation of firm and household behaviour is key to representing policy, and this is a recognized weakness of optimization and accounting approaches. Therefore respondents using B-U approaches also highlighted weak policy representation as another important limitation. Conversely, the Canadian team's approach, using a hybrid B-U model, explicitly focuses on detailed policy analysis. The wider comments reflect the tension between the development of technology-focused pathways in the long term, and simulating the role of policy in delivering the pathway in the short to medium term. This tension is a reflection of the commonly discussed opposition between normative ("what should be") and descriptive ("what is") approaches, or optimization and simulation modelling.

Mid-ranked criteria include limited representation of economics, particularly for those countries not using CGE models, and lack of spatial resolution, particularly concerning how large infrastructure change is represented, and the differences between urban and non-rural demographics and systems types. Another limitation flagged by a number of teams relates to poor representation of the industry sector, both in terms of demand driver information, and sector and technological detail. Other unranked[6] limitations raised by few teams included: limited representation of uncertainty; coarse temporal resolution, making electricity system operation difficult to model, particularly for intermittent systems; no income disaggregation, limiting distributional impact analysis; and trade effects not fully represented in country-only modelling.

3.4 Necessary improvements

The survey also asked what improvements are needed to overcome limitations. A prominent theme that emerges is that i*mproved modelling needs to ensure better linkages*. This reflects an ongoing discussion in the modelling community where on one hand you further develop models to better represent specific features of the system, e.g. behaviour of actors, power system operation, or you retain current model frameworks but link them, benefiting from their specific strengths. Three specific linkages were highlighted from the survey (and discussed more fully in section 4.2): between energy systems and CGE models, to understand wider economic

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[6] Being unranked does not imply lack of importance; subsequent to the DDPP, special related projects began related to these issues, including one to build open source accounting models, and another to address the transition from a fossil fuel to a renewables based system.

impacts; between national-scale and regional / global models, for system boundary conditions; and with environmental models, to understand co-benefits and multi-objective analysis.

A suggested further improvement would be for *enhanced access to common data,* e.g. costs for globally traded technologies, industry benchmarks, efficiency standards etc. This has three key benefits; firstly, it allows for countries with limited data availability to develop capacity quicker; secondly, it allows for established modelling teams to access useful benchmarks to check their input assumptions, and thirdly, it ensures consistency across globally determined assumptions. This also links with comments from some teams on transparency; they need to publish assumptions to ensure credibility with stakeholders but also to facilitate sharing between research teams and domestic experts. Many teams cited the need to further *develop industry sector representation.* This sector is difficult to characterise, reflecting its heterogeneous nature both within and between countries, with often insufficient data available. Another issue highlighted by different teams concerns data on population disaggregation *to explore distributional impacts,* important for considering equity issues.

For respondents working in developing country contexts, *capturing broader development objectives* is critical, in part to gain political traction. This means considering the wider impacts on the economy, including exploring the uncertainties on how economies and demographics may evolve. *Recognition of uncertainty* is also acknowledged by a number of respondents, as an important feature of pathways for decision makers to better understand. Finally, there is a recognized need to expand analyses to ensure *coverage of all GHGs*.

3.5 Summary remarks from the literature review and DDPP survey

There is roughly an even distribution between bottom-up and top-down based studies across both the literature review and DDPP, indicating they have differing yet attractive characteristics for undertaking DDPs. Pure bottom-up models struggle with representing firm and household behaviour in the face of policy as well as changes in economic structure, and top-down models struggle with technology regulations and radical technology change. It is into this niche that bottom-up and top-down hybrids have grown. All the studies have some hybridized bottom-up "technological" elements; we found no "pure" top-down CGE or econometric studies in the literature review. It can be argued that this is because deep decarbonisation requires a fundamental change in technology from the present day, and bottom-up modelling is about representation of the energy using technology stock.

Finally, (Fujino et al., 2008), (Shukla et al., 2008) and (Mathy et al., 2015), whilst undertaking similar DDP analyses, adopt a unique approach in that they all explicitly address the importance of foundational input choice as a part of scenario formation, i.e. the choice and use of those driving inputs that are not endogenous in the models but have wide reaching impacts, e.g. population, spatial structure, household formation, labour force, and even consumption preferences. In (Mathy et al., 2015) initial input choice and scenario design was put in the hands of influential stakeholders, who were asked about the acceptability of moderate and strong policies to achieve deep emissions reductions.[7] These studies suggest that in order to do DDPs, model scenario set up practices may need to evolve beyond business-as-usual calibration, followed by a technocratic policy shock, to a more systematic process of setting up alternative scenarios covering all drivers and policy levers (e.g. non-exhaustively: population growth; consumption preference evolution; taxation, subsidy and investment policies; urban planning; and direct energy and environmental policy).

4. General Insights from current DDP modelling approaches

4.1 A decision framework for undertaking DDPs

This paper has combined experiences of DDP practitioners with the literature to better understand the strengths and limitations of current analytical approaches. From this, we have developed a conceptual framework for facilitating DDP analyses, and identified where research is needed to improve the current toolset.

The DDP analysis framework (Figure 4) consists of three steps needed to determine the key characteristics and dynamics to be represented in the DDP modelling approach of a specific country, recognising the *policy priorities* to be addressed, *country system characteristic*s and *key practicalities*.

To start, the analysis must be driven by the most relevant *policy priorities*, as this determines model choice. For example, is the emphasis on assessment of GDP, trade, economic structure or income effects, which would indicate use of a hybridized CGE, or on the technological transformation of energy supplying and using sectors of the economy, which would indicate use of a bottom-up or perhaps accounting model? Or is there a strong need to incorporate issues of energy access and water security, which would indicate linkage to appropriate

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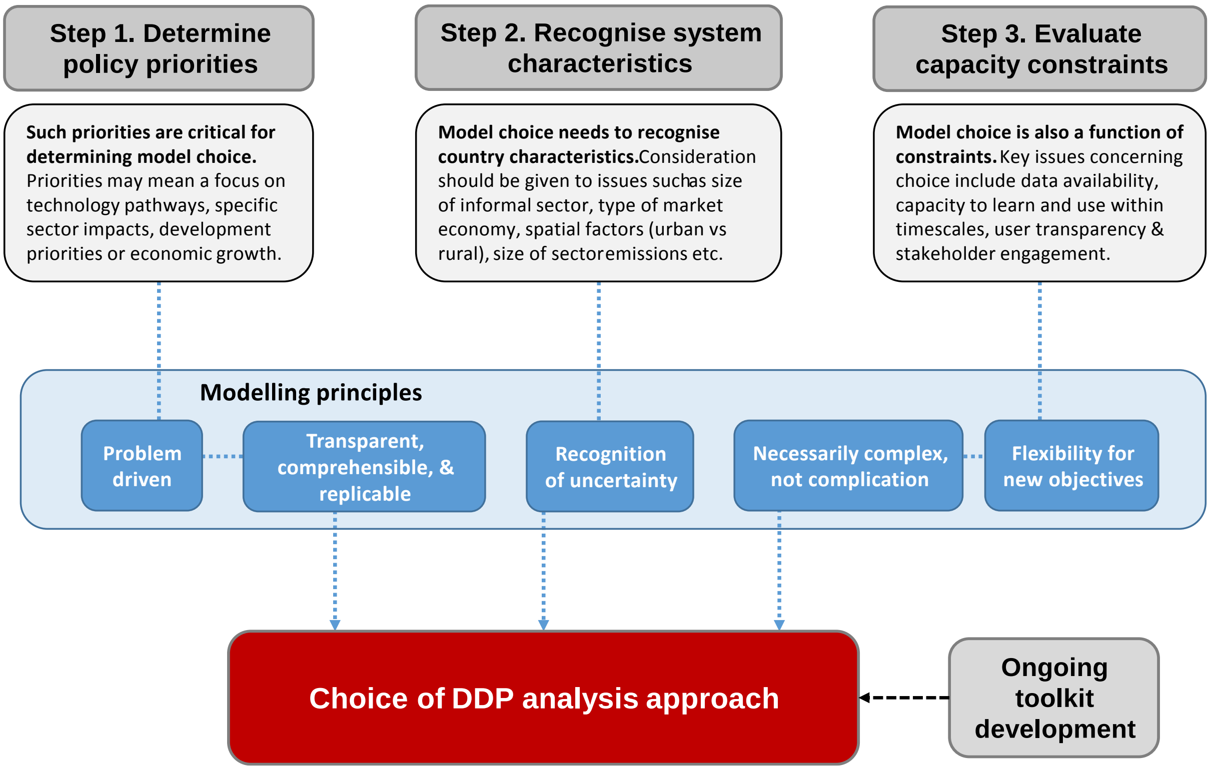
[7] This approach has also been followed by an important developing country mitigation project, currently focused in South America, called MAPS (http://www.mapsprogramme.org/).

models? While all DDPs have minimum requirements, policy priorities shift the emphasis of any given analysis. Early and effective engagement between modellers and decision makers is therefore critical.

Figure 4. Conceptual decision framework for DDP analysis



Step 1. Determine policy priorities

Such priorities are critical for determining model choice. Priorities may mean a focus on technology pathways, specific sector impacts, development priorities or economic growth.

Step 2. Recognise system characteristics

Model choice needs to recognise country characteristics. Consideration should be given to issues suchas size of informal sector, type of market economy, spatial factors (urban vs rural), size of sectoremissions etc.

Step 3. Evaluate capacity constraints

Model choice is also a function of constraints. Key issues concerning choice include data availability, capacity to learn and use within timescales, user transparency & stakeholder engagement.

Second, the chosen modelling approach must reflect *system characteristics*. If a fully developed market economy is involved, full integrated bottom-up or top-down models work, but if the economy is primarily informal, an accounting system may be more appropriate. Distinctive systems in urban and rural areas may call for spatial disaggregation, while non-climate environmental pressures could require linkages to land-water-air systems. Other factors may relate to economic systems; the presence of decision makers (e.g. individuals or households) whose criteria are not represented in the price of a good or service, or large informal economic sectors, may require simulation rather than optimisation modelling approaches.

Third, the modelling approach must recognize the need for pragmatism in determining the approach, including limitations of model ease-of-use, data availability, and practical constraints, e.g. budget, timescales, need for stakeholder engagement etc. Table 2 compares different modelling frameworks against components of the three framework steps in Figure 4.

The guidance, while subjective, reflects a distillation of literature and consultation with the DDPP researchers and other practitioners in the field by the authors.

Table 2. Comparison of DDP modelling approaches versus three key decision steps (3 stars denotes stronger application to decision driver, and 1 star a weaker application)

Decision driver	Accounting	B-U optimisation	Hybrid (B-U base)	Mixed linked systems	Hybrid (T-D base)	National IAM
1. Policy priority						
Technology roadmaps	***	***	***	***	**	*
Representing role of policy	*	**	***	***	***	*
Wider economic impacts	*	*	**	***	***	**
Development priorities	**	**	***	***	***	**
Electricity system operation	**	***	**	**	*	*
Distributional impacts	*	*	*	***	***	**
Stakeholder education	***	**	**	*	*	*
2. Country specifics						
Substantial non-energy emissions	***	*	*	**	*	*
Strong informal sector	**	*	***	*	*	*
Central control vs. competitive markets	***	**	**	*	*	*
3. Practical considerations						
Low data intensity	*	*	*	*	*	*
Low entry barriers	***	**	*	*	*	*
Use transparency	***	**	**	*	*	*
Usability	***	**	**	*	*	*

The framework itself embodies some fundamental, model agnostic principles we believe are critical if a DDP is to translate into mainstream strategic thinking. They ensure the chosen analytical framework is based on the problem being addressed, is transparent and replicable (as far as possible), accounts for uncertainties through different techniques, including scenario analysis, provides sufficient model complexity to be credible but avoids unnecessary 'black box' complication, and is flexible to address new challenges or revisit objectives. Many of these are not new, but rather reflect accepted best practices in policy analysis and modelling e.g. (Morgan, Henrion, & Small, 1992). As per Figure 4, it is crucial that decisions under the three steps are 'filtered' through these important principles.

4.2 Necessary developments in the DDP analytical toolset

The experiences of DDP practitioners, based on the literature and within the DDPP, as well as the process developed in Figure 4, help us to identify future research to aid development of the DDP analytical toolset.

4.2.1 Linked or hybridised model analyses.

Of the existing approaches, there is none that can be considered ‘best practice’; most experienced modelling teams make use of hybrid or linked frameworks, while acknowledging their flaws. It is increasingly recognized that while incremental improvements to existing tools are possible, without a fundamental breakthrough, an ‘all singing all dancing’ model may be unrealistic. (Hourcade, Jaccard, Bataille, & Ghersi, 2006) highlighted the limitations of both top-down and bottom-up approaches in providing climate policy advice, suggesting that neither could adequately capture three requirements – technology options and costs (technology explicitness), the role of policy (microeconomic realism), and wider impacts on the economy (macroeconomic completeness).

(Pfenninger et al., 2014) state that a modeller needs to consider what models are fit for purpose, and where necessary combine different models with differing strengths. The application of multi-model approaches is visible in the DDPP, where macroeconomic models were used to supplement the core analysis undertaken using B-U approaches. A key example of this is linkage to dedicated electricity models that incorporate the spatial, temporal and stock turnover complexities of the electricity system (Deane, Chiodi, Gargiulo, & Ó Gallachóir, 2012). A notable research effort exploring state-of-the-art approaches in this area is the wholeSEM project, focusing on linking between energy systems, network infrastructure, the macro-economy, environmental systems, and behavioural modelling.[8]

4.2.2 Flexibility to represent diverse energy systems.

The expansion of DDP capacity globally requires that energy models are fit-for-purpose not only in developed, market-based economies, but across a diverse set of possible systems, including systems that are not fossil fuel based, are distributed instead of centralised, and developing versus developed. (Urban et al., 2007) highlight a range of developing country characteristics poorly represented in current models - informal economies, supply shortages, sub-optimal power sector performance, structural economic change, electrification issues, traditional bio-fuels, and the urban–rural divide. They suggest improved models should follow

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[8] http://www.wholesem.ac.uk/

a bottom-up or hybrid approach (rather than pure top-down) and use simulation or toolbox modelling, rather than optimisation. (Pandey, 2002) adds that top down approaches may provide necessary insights on the economic 'effects of long-term policies with respect to investments, market structures and technological progress'.

4.2.3 Recognising wider environmental constraints

In many countries, energy systems are inextricably tied to wider water, land, and air systems. These linkages need to be better recognised and understood, both to understand physical system constraints, and the impacts of future energy choices on natural systems (Howells et al., 2013), (Bazilian et al., 2011). Often the co-impacts of lower carbon energy systems are beneficial, and therefore critical for making the policy case (Mundaca et al., 2010). For example, some useful approaches in relation to the European policy interface between air quality and climate change have been developed under the EC4MACs modelling framework (Nguyen, Wagner, & Schoepp, 2012).

4.2.4 Data harmonization and availability

During the DDPP project a key area of effort was standardization of the date of availability, performance and detailed upfront and operating costs of key technologies, and accounting for global learning effects, e.g. decarbonized electricity generation technologies, low emission vehicles etc. There is an outstanding need for commonly held and used technology data in the DDP modelling community and the energy modelling community at large.

4.2.5 'Entry level' toolsets (including data) for expanding DDP capacity.

To expand capacity to do DDPs, particularly in developing countries, effective and accessible (zero to low cost, easier to learn, usable, transparent) *entry level tools* and data are needed to allow for rapid and extensive capacity development. These provide the basis for quick and efficient analysis, as well as providing a stepping stone to more sophisticated modelling tools. Areas for improving entry level accounting frameworks include electricity system operation, supply-demand balancing, sector integration, and expansion to non-energy sectors. This capacity has and continues to be developed by the DDPP consortia and the LEAP community (IGCS, 2014).

4.2.6 A focus on transparency, engagement and communication.

To have the necessary impact on policy, modelling analysis needs to be transparent, encourage verification, validation, and replicability as far as possible (Mundaca et al., 2010), provide for opportunities for stakeholder engagement, and be effectively communicated. On verification, (DeCarolis, Hunter, & Sreepathi, 2012) argue that, given that non-predictive energy models can never be completely validated, there is an even greater need to allow for replicability, although this is not current practice. New tools that are fully open source with low entry costs are emerging, such as OSeMOSYS (Howells et al., 2011), community efforts and norms are developing in this direction,[9] and established modelling teams are pushing for greater transparency.[10] Learning from other disciplines on presentation of complex data is also required, particularly in relation to multiple scenarios and uncertainty metrics.

5. Conclusions and recommendations

This paper makes a contribution to the literature by providing a critical review of DDP-type analyses, with a focus on the models used. It finds there are a range of analytical tools being used to formulate DDPs, all with strengths and limitations. A framework is proposed that attempts to tie the experiences of practitioners together, by formulating three clear steps for guiding analytical framework choice and implementation: assessment of policy priorities, country system characteristics and practicalities.

Improving tools and expanding DDP capacity requires funding. A key recommendation of this paper is for research funders to target resources at those areas highlighted as deficits. This includes model linking, flexibility to handle a range of current and possible energy systems, recognizing and incorporating wider environmental constraints, incorporating behaviour and policy impacts, data availability and standardization, and development of entry levels tools. Development in all areas is key to making these analyses more policy relevant. Given the large-scale investments that DDPs could help guide, additional funding to develop models is a very cost-effective use of resources.

Whatever tools are used, it is important the focus be on transparency, engagement and communication, all critical for the acceptability of DDPs by decision makers, and their integration into strategic planning and policy packages. Without this, further improvements across modelling approaches will not necessarily translate into the stronger national ambition and policy action needed to drive deep decarbonisation.

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[9] For example, the OpenMod initiative, http://wiki.openmod-initiative.org/wiki/Main_Page

[10] UK initiative to make TIMES open source. http://www.wholesem.ac.uk/wholesem-news-publication/uktm-collaboration

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