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CONCEPT NOTE

ASSESSMENT OF FUTURE ENERGY DEMAND

A methodological review providing guidance to developers and users of energy models and scenarios

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PREFACE

Many countries have embarked on an energy transition that depends heavily on renewable energy sources. Some are also working to phase out nuclear energy. Others are shifting from coal and/or oil to natural gas, until such time as widespread reliance on renewables is seen as feasible and affordable. These transitions and policies for managing them are informed by a diverse set of scenarios, not all of which provide consistent outcomes and perspectives. In particular, there is no consensus as to whether the "extraordinary" curtailment in energy demand, as described by prospective and ambitious energy scenarios on energy efficiency, is attainable. At least for mature countries, these scenarios project economic growth without per capita increase in energy consumption. On the other hand, concerns about energy access and security, affordability and sustainability remain high on the agenda of both public and policy debates.

Against this backdrop, IRGC began project work on "**Energy Transitions: Demand Anticipation and Consumer Behaviour**" in 2014. In line with IRGC's focus on risk governance, it is motivated by the fact that large-scale energy transitions or transformations of energy systems that are to take place over the next few decades will redefine risks and opportunities within the energy and other sectors. Ability to anticipate such changes is crucial. But, while decision makers rightly use scenarios to inform their strategies and policies, many scenarios provide a false sense of confidence in projected or narrated evolutions of energy systems.

The focus on demand anticipation and consumer behaviour is informed by the realisation that scenarios have traditionally focused on the supply side of energy systems while behaviour and end-use demands have received less attention. Also, failure to properly anticipate changes in the way energy will be consumed by different economic and social segments during and after the transitions constitute a major risk to private and public investors (including investment in the wrong technology) and policy makers (e.g. inability to maintain energy security).

In this context, IRGC and its partners, Helmholtz-Alliance Energy Trans and the Center for Climate and Energy Decision Making of Carnegie Mellon University, hosted on 9-10 October 2014, a workshop entitled "**Demand Anticipation: Improving Methods to Assess Future Energy Demand**." The objective was to review different types of scenarios and modelling approaches to better anticipate the demand and to provide methodological guidance for developers and users of models and scenarios. The overarching goal is to help improve the governance of energy transitions.

This Concept Note, originally prepared as a background paper to the workshop and subsequently updated, is written for an audience of energy modellers who develop models and scenarios, and decision-makers who commission or use them. It describes the mainstream energy scenarios and modelling approaches to illustrate the state of the art, and to stimulate thinking as to how these approaches can be used and improved for better assessment of energy demand.

The Concept Note suggests that there is a need for more sophisticated energy demand models and/or better scenarios, in particular using insights from Behavioural Sciences. IRGC also draws attention to the ways scenarios are being developed and used (and abused), and describes in broad brushstrokes different approaches for improving the usefulness of models and scenarios, and for making robust decisions in face of deep uncertainties regarding scenarios and modeling outcomes.

IRGC Concept Notes are publications that set the scene for a certain governance challenge, raise questions and prepare further work. They are primarily based on literature review and some discussion with experts, but they are not meant to provide policy recommendations.

Abbreviations

ABM	Agent-based modelling
DLR	Deutsches Zentrum für Luft- und Raumfahrt
EFOM	Energy Flow Optimization Model
EIA	U.S. Energy Information Administration
IAM	Integrated Assessment Model
IEA	International Energy Agency
IIASA	International Institute for Applied Systems Analysis
IPCC	Intergovernmental Panel on Climate Change
HERMES	Harmonized Econometric Research for Modelling Economic Systems
MARKAL	Market Allocation
MEDEE	Modèle d’Evolution de la Demande d’Energie
NEMS	National Energy Modeling System
PRIMES	Price-Induced Market Equilibrium System
SAS	Story-and-Simulation
SRES	Special Report on Emissions Scenarios
TIMER	Targets IMage Energy Regional
TIMES	The Integrated MARKAL-EFOM System
VLEEM	Very Long Term Energy Environment Model
WEC	World Energy Council

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EXECUTIVE SUMMARY

Prior to choosing what direction to follow in making an energy transition, decision-makers look to scenario-makers for advice on the economic and environmental consequences of alternative energy-transition pathways, energy-related policies, energy-mixes and any other intervention that might improve the transition process. One of the mainstays of current transitions, such as the German *Energiewende*, is the decoupling of energy consumption and economic growth by way of energy efficiency and, in some cases, energy sufficiency measures. These require both technological and behavioural changes. They underline how current energy transitions are not simply technological transitions but also socioeconomic transitions.

Many large-scale scenarios – at global level (e.g. IEA 450 ppm Scenario[1], WWF World Scenario[2]), regional level (e.g. EU 2020 Climate and Energy Package[3], EU 2030 Framework for Climate and Energy Policies[4] and 2050 Roadmap[5]) and national level (e.g. Swiss Energy Strategy 2050[6], UK Carbon Plan[7]) – help frame **visions on future energy system**s. The majority of these scenarios focus on future energy mixes with a view to re-balancing the respective shares of energy sources, for example increasing the share of renewable energy and decreasing energy-related greenhouse gas emissions.

However, few of these scenarios address novel drivers of energy consumption in a deliberate and comprehensive manner. Demand forecasts and projections have also often been criticised for being consistently inaccurate. Errors in forecasts tend to grow over time because of uncertainties associated with the impact of policy and unexpected changes in drivers such as the prices of energy. The Concept Note does not address these forecast errors but is instead informed by the specific need for many countries engaged in energy transitions to shift to low-energy consuming economies without sacrificing living standards. This requires profound **behavioural and organisational change**, encompassing technology shifts and implementation, which can be facilitated by lifestyle changes, including consumption behaviour (such as the use of energy-efficient devices), and the way consumers interact with energy providers. **Scenarios and models need to account better for potential changes in future energy needs and energy services and the ability of policy to shape future demand**.

In this context, the Concept Note reviews the main **types of energy scenarios and models** currently used to anticipate energy demand and inform energy transitions. It highlights their limitations, in particular the uncertainties associated with assessing future demand, and underlines emerging trends that incorporate insight provided by behavioural economics. **If the odds of achieving the goals of current energy transitions are to be improved, it will be crucial to improve energy scenarios and models**.

This paper firstly provides information for decision-makers who commission and use scenarios as well as energy system modellers. It places the emphasis on energy demand anticipation. Secondly, it highlights important considerations for those developing and using energy scenarios for policy and strategic decision-making. It suggests that scenario developers devote more attention to understanding and quantifying energy demands and their associated services and highlights relevant approaches.

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[1] A scenario presented in the World Energy Outlook that sets out an energy pathway consistent with the goal of limiting the global increase in temperature to 2 °C by limiting concentration of greenhouse gases in the atmosphere to around 450 parts per million of CO_2.

[2] A provocative scenario of the World Wildlife Fund that aims at a world that runs entirely on renewable energy by 2050.

[3] A set of binding legislation, which aims to ensure the European Union meets its climate and energy targets for 2020.

[4] An integrated policy framework for the period up to 2030 that ensures regulatory certainty for investors, and provides a coordinated approach for Member States.

[5] A guide outlining plausible ways to achieve an 80% reduction target from a broad European perspective.

[6] A strategy to restructure the Swiss energy system by 2050 excluding nuclear power generation.

[7] UK government's plans for achieving the reduction in emissions that it has committed to, including actions and milestones.

Broad scenario categories and development approaches

The Concept Note provides an overview of three broad categories of scenarios: forecast, exploratory and normative.

Forecast scenarios are typically quantitative scenarios based on historical trends. They incorporate the effect of current policy measures based on known causes and effect relationships between policy and impact. Forecast scenarios, such as those developed by the EIA[8] and the IEA World Energy Outlook[9], can offer reasonably good short-term predictions, but they become increasingly uncertain over time.

Exploratory scenarios can be either qualitative or quantitative. They take into account expected policy measures, the effect of medium-term changes in current and new policy, as well as surprising events (wildcards). Examples include the World Energy Scenarios of the World Energy Council[10] and the Shell Energy scenarios.

Normative scenarios are based on an anticipated vision of the future. They map out various designs of the vision, such as those of the IEA 450 ppm scenarios or the Greenpeace Energy Revolution scenarios[11], and use a "backcasting" approach in order to link short-term actions with long-term strategic objectives.

In addition, there are various types of **hybrid scenarios** that combine normative and exploratory scenarios and qualitative and quantitative approaches. **Sociotechnical scenarios** constitute an emerging class of hybrid scenarios based on the premise that **the embeddedness of energy technology in society can shape the future of our energy systems**. Sociotechnical scenarios are quantitative scenarios modelled on the basis of qualitative scenarios that provide narratives and storylines of plausible futures. Sociotechnical scenarios have been developed following the critique that energy models generally do not sufficiently reflect social and political developments. Taking these into account can help develop more robust strategies and policies. In Germany, the Helmholtz Alliance Energy-Trans is involved actively in building such scenarios.

In general, initial work for scenario development is based on literature review and expert elicitation. Many institutions are also turning to participatory exercises to elaborate energy scenarios. In the context of energy transitions and sustainable development, the ensuing **participatory scenarios** respond to the increasing need to involve relevant stakeholders at an early stage of decision-making. This approach provides a platform for different actors – from industry, government and the public – to better understand other actors' perspectives, thus stimulating social learning and triggering systemic thinking. The French National Energy Debate illustrates the application of participatory scenarios through civil society engagement to inform the Energy Transition in France.

Modelling energy demand

Energy models provide information that is often integrated in the process of developing qualitative scenarios, and also allows the generation of quantitative scenarios. Models are broadly classified as top-down (macroeconomic), bottom-up (techno-economic / engineering), or hybrid (energy-economy). Different models have been developed for various uses and for specific contexts. In some of these models, energy demand is developed outside the energy models on the basis of major drivers such as income and population growth. In others, an endogenous approach is taken. The choice of model for specific end-uses is very important because energy transitions involve systemic effects at various levels. Inaccurate representation of energy demand in models can lead to poor policy analysis and prescriptions.

Top-down models, due to their macroeconomic nature, are particularly suitable for assessing the impact of energy-related policies on economic welfare. Demand is primarily driven by economic activity and population growth, which assumes either market equilibrium or slow-adjustment to equilibrium. Because top-down models are often aggregated models of energy demand and supply, they are less suited to assessing demand for different energy carriers and services. Bottom-up models are more adapted to that end.

Bottom-up models are techno-economic models that have extensive technological details by way of different

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[8] Projections of the U.S. Energy Information Administration's (EIA's) *Annual Energy Outlook 2014*, on the factors that shape the U.S. energy system in the long term.

[9] International Energy Agency's (IEA) projections of energy trends through to 2040.

[10] The report "Composing Energy Futures to 2050" assesses two contrasting policy scenarios.

[11] Pathways for achieving climate goals through investment in renewable energy.

levels of sectoral disaggregation (e.g. transportation, industry, residential and commercial) and further sub-sector disaggregation. For example, the IEA Energy Technology Perspectives (ETP) provide finer levels of sectoral analysis from which insights can be fed into the IEA World Energy Model – a bottom-up model – that is used for the IEA World Energy Outlook. The extent of sectoral disaggregation needs to be aligned with the policy and strategic issues at hand. Policy relevance is also influenced by the spatial and temporal resolution of the models, including the extent and nature of market segmentation. Appropriate spatiotemporal resolution is particularly important for capturing the dynamics of renewable resources.

Most models used for informing energy transitions are of the **hybrid-type**, combining the macroeconomic view of top-down models with details of energy technologies in bottom-up models. Energy models are continuously being improved to address policy and strategy needs. **One emerging trend is towards improving the microeconomic explicitness of models in light of behavioural economics**.

Behavioural models

In energy models, demand is often represented by means of conventional demand functions (e.g. GDP, growth and demography) and energy intensities (annual consumption per capita or per unit of GDP). Behavioural changes due to changes in social practices (e.g. driving behaviour) or structural changes (e.g. the rise of car-sharing) or technological changes (e.g. energy efficiency) are usually either grouped together or represented in conventional ways according to end-uses. When planning for transitions that span several decades, models can have serious limitations if they do not account for new behavioural patterns that unfold/emerge and have a significant impact on energy demand.

Attempts at improving the behavioural realism of models focus on representing different forms of behavioural features through parameters and variables such as:

- Discount rates. Time discounting and time preference help assess temporal trade-offs between the short-term and the long-term, influencing investment decisions at various scales. The quality and reliability of energy demand assessment can possibly be improved through a more rigorous choice of discount rates.
- Market heterogeneity, to account for different preferences across consumers and businesses. Business behaviour, human behaviour and social preferences, encompassing institutional and jurisdictional frameworks, supply-chain bottlenecks and social barriers can be important factors that influence the scope for converging to equilibrium points defined in models.
- Disutility costs, for example, range anxiety and charger stations availability for electric vehicles.

More theoretical and applied work is needed to expand on the major behavioural changes that drive new energy consumption patterns, and could possibly stimulate the transition from high-energy consuming to low-energy consuming economies, as well as the drivers of these behavioural changes (e.g. prices, technology, structural changes in society, policies, individual preferences, energy services). Options for improving the behavioural realism of models are being explored by various institutions, such as the EIA and IIASA. Prior efforts encompass work to include consequences of the rebound effect in energy efficiency.

Improving energy scenarios and models to account better for uncertainty

It is difficult to reduce many uncertainties in energy systems because some of the key parameters such as oil prices, technology competition, etc., although critical to energy models, are extremely difficult to predict. This uncertainty is often insufficiently recognized and communicated. There are however possibilities for energy scenario and model improvement, including:

- Better accounting for complexity or realism (e.g. adding more variables).
- Understanding which model parameters can be modified to capture the critical uncertainties that affect demand.
- Including knowledge about the evolution of energy-related regulatory frameworks.
- Understanding which key parameters can truly be considered as independent and how these can evolve realistically.

There are also modelling tools that can help deal with uncertainty (to the extent that it is reducible or relevant for decision-making purposes). Examples include:

- **Cross-impact analysis**, which provides a coherent and transparent approach to integrate interdisciplinary sources of knowledge analytically in scenario development. It allows a systematic study of combinations of input parameters, hence making the uncertainty and complexity of societal (and non-quantifiable) factors more explicit.

- **Agent-based modelling**, which helps address the uncertainty and complexity that result from more realistic models of energy system transformations, e.g. by embedding technological development within societal contexts.
- **Stochastic simulation**, which deals with uncertainty by testing different possible parameters within a possible range of values using Monte-Carlo simulation or similar approaches.

Usefulness and limitations of models and scenarios for energy planning

The diversity of scenarios produced by different organisations reflects divergent views on determinants of energy futures such as economic growth, the role of business, the extent of social adaptation and the role of possible transition leaders. Recommendations from a workshop for scenario developers and modellers together with a review of relevant literature conclude that in view of the diversity of models, it is important to:

1. **Choose models that are fit for purpose**. For instance:
   - Macro models (based on econometric modelling or general equilibrium analysis) may be more appropriate for national level planning, while micro-models are more suited for socioeconomic analysis.
   - Potentially, it is better to analyse factors that influence energy demand such as employment effects, rebound effects from energy efficiency policies and location of industries using top-down (macroeconomic) models rather than bottom-up (techno-economic) models.
   - Use models that are appropriate for different time horizons. Some researchers have suggested that for short-term perspectives, top-down econometric-based models may be more appropriate and make some predictions feasible. For medium-term outlooks (20-30 years) and policy assessment, top-down models may be preferable. For longer-term planning (50 years) such as for current energy transitions, bottom-up models may be more suitable. When the system is likely to undergo intermittent technological and socioeconomic shifts, the emphasis should first be put on building qualitative and internally consistent pictures of plausible energy system development, then on quantification.

2. Carefully **match models with relevant scenarios** and vice-versa. The risk in quantifying scenarios (narratives and storylines) with inappropriate models is that the analyses and recommendations generated are incongruous and raise controversy among both the community of researchers and the decision-makers.

3. **Assess uncertainty and biases in energy scenarios and forecasts**. Because they are likely to persist, it is critical to identify the multiple traits of uncertainty and biases as they are embedded in data, model and foresight exercises. The goal is to reduce uncertainty in critical parameters, which, in turn, increases reliability in energy modelling and ensures that vision is less open to criticism.

4. **Communicate scenario and modelling outcomes adequately**. Model-based scenarios can provide helpful and important decision support. To enhance the usefulness of their work, modellers should ensure that the underlying assumptions (such as the effect of induced technological change and heterogeneous behavioural responses to policy) and model uncertainties are well communicated so that they can be integrated in the decision-making process. Furthermore, communication on outcomes such as energy consumption levels, volumes of greenhouse gas emissions, and policy variables (e.g. tax rates) should be communicated in simple terms to policy-makers and other stakeholders.

5. **Engage multiple stakeholders in the development of scenarios**, in particular for backcasting and sociotechnical scenarios, in order to steer upstream discussion of desired outcomes of transitions, opportunities and challenges, as well as steps to achieve the objective.

Conclusion

When planning energy transitions it is paramount to determine the evolution of energy demand. This requires a multidisciplinary approach to understand the many drivers of transition that result in a low-energy-consuming economy. It is also important to integrate broader regional and international contexts in national plans for energy transitions. Such an inclusive approach poses challenges to both scenario developers and modellers because of a number of crosscutting issues that are often hard to quantify because there is no historical precedence. There is a growing interest for research in this field, which decision makers are invited and encouraged to follow so that decisions in relation to energy transitions can be improved.

1.

INTRODUCTION

In their task of drawing up a strategy for a transition to more secure, equitable and sustainable energy systems (WEC, 2008), decision-makers are faced with much uncertainty as to the future evolution of energy demand and supply. They therefore turn to scenarios. The Intergovernmental Panel on Climate Change (IPCC) defines scenarios as "a coherent, internally consistent and plausible description of a possible future state of the world". A scenario is not so much a forecast as an "alternative image of how the future can unfold." Energy scenarios aim at providing a comprehensive view of the impact of different developmental trends on the likely evolution of the energy system and potential outcome of energy systems' variables and performance indicators. Different scenarios – and models underlying these scenarios – provide a range of scientific evidence, which are not intended as predictions or policy recommendations but rather to inform decision-making.

Contemporary energy scenarios are driven by a combination of macroeconomic trends, the current understanding of policies and rates of technological change, and climate change considerations. Certain factors are often ignored or underestimated in energy scenarios. These include: (i) the influence of socioeconomic, cultural and demographic structures on the energy market and the adoption of new technology; (ii) the pervasiveness of legacy and maladapted infrastructure, and (iii) low-predictability, high-consequence events (or shocks) such as the discovery or exploitation of new energy sources[12] (Stout, 1998). It is necessary to acknowledge that some uncertainty will always remain to avoid foolhardy mistakes when using scenarios in planning for and governing energy transitions.

Generally, existing models that inform energy scenarios, or which are used to quantify scenarios, are typically better at characterizing the supply side of energy systems than that of demand. As a result, mainstream scenarios tend to underestimate the influence of social trends and behaviour on energy use. There is, in effect, increasing recognition that the demand side is not sufficiently taken into consideration, in particular concerning "technology adoption, the complexity of choice-making, and the human-dimensions of energy use and environmental change" (Sovacool, 2014). This too is true in respect of more general behavioural perspectives that relate to the behaviour of policy-makers, consumers and utilities. Extrapolating from the observation that, in the past, energy models have adapted to external circumstances and needs (see below), research can help develop new insights, informed by behavioural economics, to address the aforementioned shortcomings in current scenarios and models. Some organisations such as the EIA and IIASA are already working in that direction.

Figure 1 shows the rising trend in global energy consumption and major transitions between 1800 and 2010. The transition to coal from biomass is by far the longest tran-

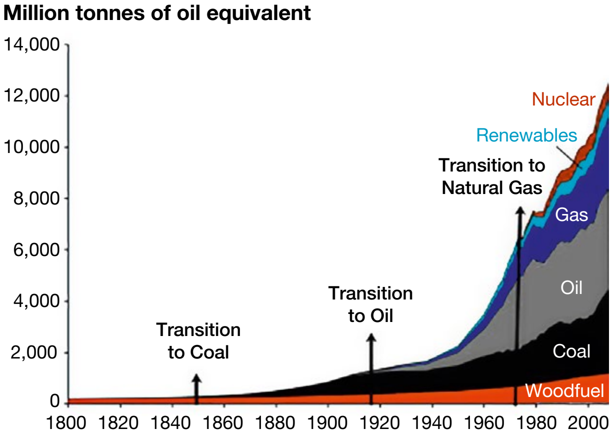

Figure 1: Global primary energy consumption and transitions, 1800-2010.
Source: Fouquet (2009) in Fouquet and Pearson (2012)

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[12] For instance, the large-scale development of unconventional gas and oil was unforeseen and therefore not factored into scenarios one or two decades ago.

sition, also marked by the Industrial Revolution and the beginning of a new era of prosperity and growth in energy consumption. The second transition is that of coal to oil. The first energy scenarios were developed in the 1950s, i.e. during an era of modernization, and energy models were embedded in the physical reality of energy systems. The techno-economic models of the 1970s were based on macroeconomic premises and the prevailing neo-classical economic paradigm, and were developed in response to the oil crisis[13], which also prompted a 'transition' to natural gas. Shell scenarios, beginning in 1965, constituted a marked departure from the premise of historical knowledge and extrapolated trends to more descriptive scenarios based on disciplined imaginations or visions of the future, respectively exploratory and normative scenarios.

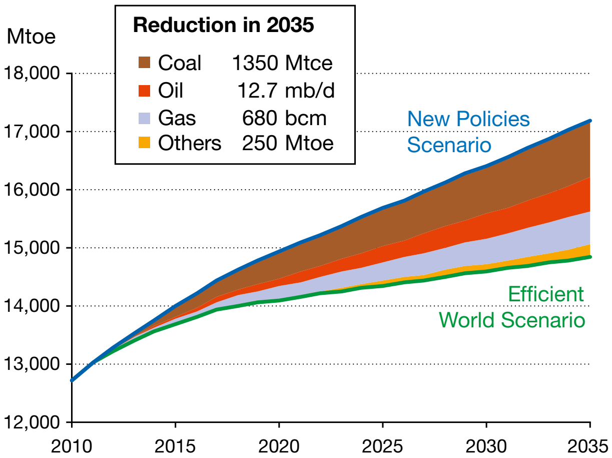

Figure 2: Total primary energy demand 2010-2035.
Source: Adapted from IEA-WEO (2012)
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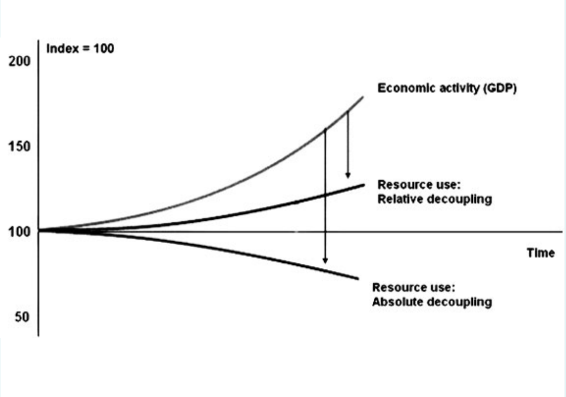
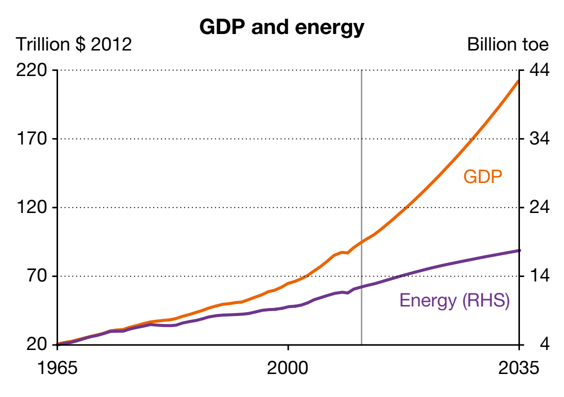
Figure 2 shows projected global primary energy demand up to 2035 following two different scenarios, both of which indicate a break from the unprecedented increase in demand over the past 50 years. The green line shows the ambitious objective of curtailing energy demand to halve energy demand growth by 2035. This may constitute one of the major challenges of current energy transitions, since reduced growth in energy consumption should not have to be at the expense of economic growth or to the detriment of the environment. Economic growth that is accompanied by a reduction in energy demand is only feasible if energy demand is decoupled[14] from economic growth through energy efficiency (see Box 1) and energy sufficiency. At the same time, climate change remains high on the agenda (see Figure 3). Figure 3 shows the global energy-related carbon-dioxide (CO_2) emissions for four different scenarios for OECD and non-OECD countries. The red line shows CO_2 projections under current policies; the blue line indicates corresponding predictions for expected policies not yet in place. The Efficient World Scenario's predictions (dashed line) reflect the results of adopting current and proven technologies to improve energy efficiency. The 450 Scenario are projections (green line) associated with the normative vision of an upper limit of 450 parts per million (ppm) of CO_2 in the atmosphere.

Box 1: Decoupling between energy consumption and economic growth



Source: Raworth (2012)



Source: BP (2014)

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[13] Note that the IEA was established in the wake of the 1973 oil crisis.

[14] Relative decoupling means that energy consumption may increase but at a slower rate than economic growth. Absolute decoupling is achieved when energy use declines over time while the economy grows.

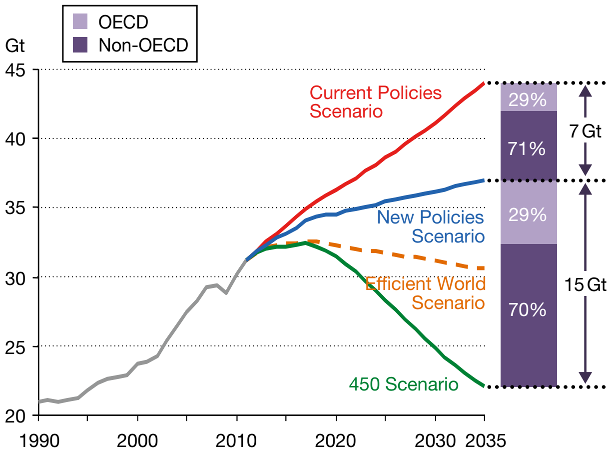


Figure 3: Global energy-related CO_2 emissions by scenario. *Source*: Adapted from IEA-WEO (2012). © OECD/IEA 2014, IEA Publishing

As a result, the large-scale energy transitions or transformations of energy systems over the next few decades will lead to substantially redefined risks and opportunities within the energy sector. Planners will need to develop new assumptions concerning drivers of change and how demand is likely to evolve. Existing and mainstream approaches to assessing future energy demand – i.e. those based on income, energy prices, population growth and demography – may well be inadequate.

2.

IS THERE A NEED FOR MORE SOPHISTICATED DEMAND MODELS / SCENARIOS?

The unprecedented nature of current energy transitions makes managing present transitions on historical knowledge and historical dependencies in energy models impossible. There is a perceived need for more behavioural or microeconomic realism in energy demand models and scenarios, which lies in the differences between past and present (and prospective transitions). In particular:

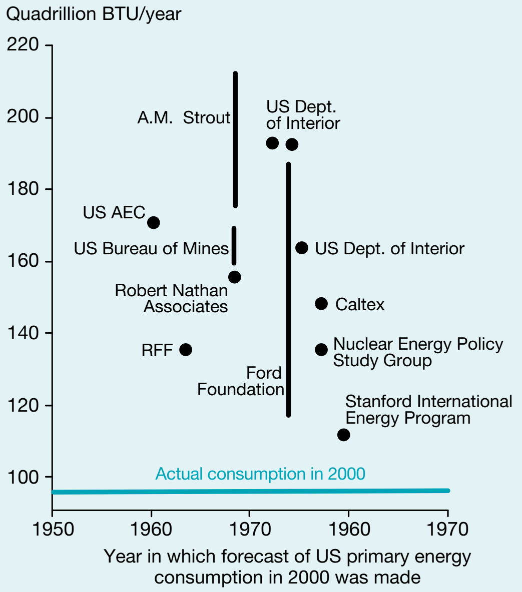
- **Anticipated transitions, at least in Europe, entail limiting highly polluting energy sources (some of which were instrumental in past transitions and may remain a linchpin in current transitions as in the case of German *Energiewende*); introducing thrifty energy consumption measures, while conserving consumer sovereignty and sustainable lifestyles. By contrast, past transitions were driven by fossil (polluting) energy sources and were accompanied by increases in energy consumption, in turn fuelled by economic growth and economic prosperity.**
- **The progressive liberalization of retail energy markets also implies growing consumer options and modified energy market dynamics that are not captured in more general aggregate demand models.**
- **Demand-side developments such as demand adaptation, co-generation and storage for own consumption, whether at plant or household level, are likely to be energy-game changers for realistic rates of technological progress.**

To understand the impact of these developments, the question is, on one hand, whether forecast/projection models should be more sophisticated and, on the other, whether energy models and scenarios where the epistemological basis follows techno-rationalistic and economically motivated paradigms need also to include ecological – and, when not the case, to what extent – and behavioural dimensions of energy systems. In this respect, attempts at determining the likely evolution of energy demand have often failed.

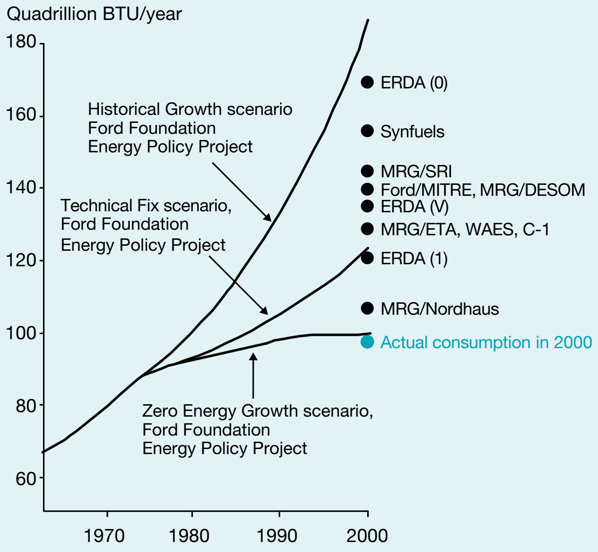
2.1 Energy demand projections often go widely astray

Prior research has shown that energy-forecasting scenarios have often seriously misjudged energy demand (Morgan and Keith, 2008). The leftmost plot in Box 2 shows the summary of forecasts of primary energy consumption in the US for the year 2000 compiled by Smil (2003) as a function of the date on which they were made. The rightmost plot compares the forecasts of primary energy consumption in the US in three scenarios developed by the *Ford Foundation Energy Project* as well as other studies, compiled by Greenberger (1983), reported in the diagramme. Except for Ford Foundation's *Zero Energy Growth Scenario*, all scenarios projected much higher energy consumption. Although it displays the smallest prediction error, the Zero Energy Growth Scenario may not have captured the actual driver(s) of the low-energy consumption path. Besides, the results of these energy scenarios should not be interpreted as forecasts.

Box 2: Poor performance of past predictions of energy consumption in the US



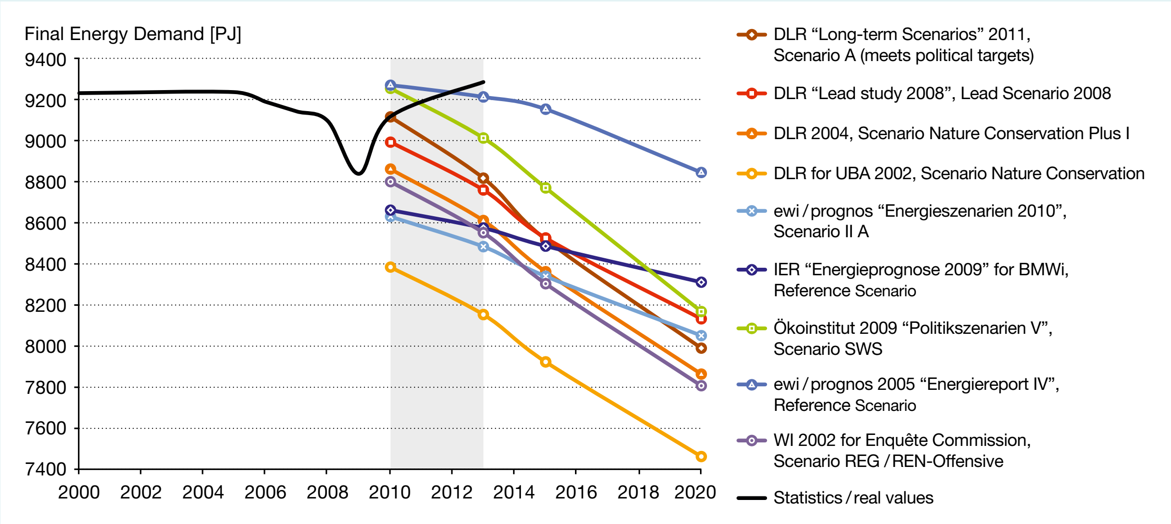
Source: Smil (2003)



Greenberger (1983), adapted from Morgan and Keith (2008)

In contrast to the previous US example, since 2002, most energy scenarios for Germany (as listed in the plot in Box 3), have systematically underestimated energy demand. The black line starting in 2000 corresponds to actual energy demand in Germany until 2013 (in petajoules (PJ)). The other lines correspond to model-based projections commissioned by the German government to inform the 2010 energy reform plans as well as some earlier projections. The varying rates of decline across scenarios are possibly due to different assumptions or the different models used to generate these figures. (Including the drivers of the differences is beyond the scope of this Concept Note.) However, what is of particular concern is that such an underestimation of demand, unless demand is curbed in the near future, may undermine any chances of the German *Energiewende* succeeding as described in the next section.

Box 3: Systematic underestimation of final energy demand in Germany



Source: DLR Analysis (personal communication)

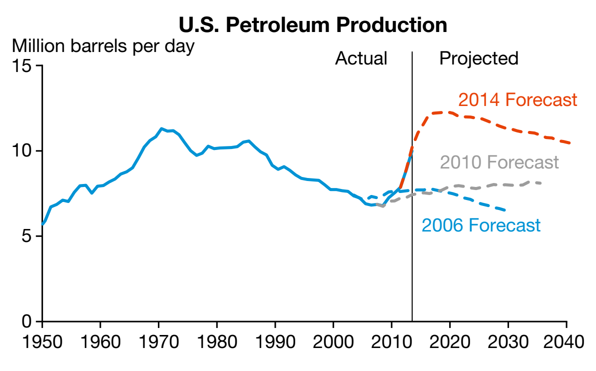
2.2 Risk associated with inadequate uncertainty analysis and communication

Many scenarios and models do not emphasize uncertainty sufficiently. As mentioned earlier, Morgan and Keith (*op. cit.*) advocate using probabilistic estimates as opposed to point estimates. They also argue that while scenarios can be helpful, they can often be misleading since compelling storylines and narratives can make decision-makers more susceptible to availability bias. Often scenario developers and modellers are aware of the uncertainty, but fail to communicate it adequately to users who rely on the scenarios. This can result in poor decisions and even policy failures, where the expected outcome of policy measures is not reached. The risk of policy failure can be exacerbated by systemic negative externalities (see Box 4).

Systematically underestimating actual energy demand as reflected in the energy scenarios for Germany (Box 3) also leads to policy risks and the chance that energy systems will not perform as expected. For instance, projections that show a decline in energy demand can result in an underestimation of the effort required on the supply-side. Switching to renewable sources and reducing demand by means of greater efficiency is one of the fundamentals of the German Energiewende since the resulting energy efficiency contributes to a reduction in CO_2 emissions ceteris paribus (i.e. everything else remaining unchanged). Projections of a continuous decline in demand reduce the incentive to increase investment in renewables, especially when this is costly. The currently observed gap between actual and projected energy demand is indicative of potential shortcomings in the demand scenarios, which, if translated into policy optimism, could undermine the Energiewende efforts.

Box 4: Consequence of using wrong forecasts

Long-term forecasts are often incorrect due to unexpected events or, for instance, when uncertainties are underestimated. Erroneous forecasts can stem from (i) variations in relative fuel prices, (ii) changing policies and regulations, (iii) faster or slower technological progress and technological breakthrough, and (iv) changing demand patterns and levels. One example of the latter concerns the change in driving habits (Dutzik and Baxandall, 2013) and policy-induced vehicle fuel-efficiency gains that led to forecasts of motor gasoline consumption in the U.S. going astray (see figure below.). But does it matter?



Source: EOP (2014)

Erroneous forecasts can have real policy consequences, which may backfire. For instance, the 2007 US Renewable Fuel Standard (RFS), mandating higher biofuel production, was based on forecasts of continuous growth in the use of gasoline. It led to a rapid expansion of the production of corn ethanol in the U.S. But, gasoline use stagnated, adversely affecting not only the refineries concerned but also other biofuels markets, where growth was desirable, but stalled due to the initial spike in ethanol (Schnepf and Yacobucci, 2013). **Such negative cross-market externalities are often hard to predict**.

2.3 Options for improving energy demand scenarios

From a modelling and scenario-making perspective, there are several possibilities for improving anticipation of energy demand. The way forward will depend largely on the policy or strategic questions.

2.3.1
New representations of energy demand: useful energy and embodied energy

In 2007, the IEA (2007) explored the possibility of modelling energy end-use or energy services and deriving energy demands for different energy efficiency scenarios. Ayres and Voudouris (2014) show that this approach, in allowing economic development to be linked to the evolution of useful energy rather than energy demand, is more suitable for decisions such as assessing technological pathways.

In the same manner, Pourouchottamin et *al*. (2013) explore the concept of embodied energy – all energy that is used either directly or indirectly for supplying goods or services – to provide new representations of energy consumption. The authors contend that embodied energy has the advantage of highlighting the energy content of societal consumption as well as the social dimension of energy transition.

2.3.2
Behaviourally realistic energy demand models

Improving the behavioural realism of energy end-use models can be achieved in at least two ways. A first approach involves adding behavioural drivers such as disutility costs, social and environmental preferences to existing models, or even making some parameters endogenous. This approach can play a significant role in increasing the complexity of existing models or even require a wholesale replacement of models. A second approach is to identify model parameters, some of which may be inherently uncertain, where quantification may be improved based on understanding of human behaviour as informed by behavioural economics, e.g. different discount rates for different households, which vary according to factors such as lifestyle and savings behaviour. By altering existing model parameters, greater demand segmentation can also substantially increase the complexity of models.

Further theoretical[15] and applied work – along the lines of those being pursued by IIASA[16] and the EIA (2014) – is needed to clarify the major *behavioural changes* behind *new energy consumption* patterns. These might possibly stimulate the transition from a high-energy consuming economy to a low one. It is therefore important to also understand the *drivers* of these behavioural changes (e.g. prices, technology, structural changes in society, policies, individual preferences, energy services) (see Section 4.3).

It is important to assess the impact, e.g. in terms of policy relevance, of modifying demand models, whether by adding variables or by altering parameters. Given the potential increase in complexity, the question is therefore how and to what extent the behavioural realism of models needs improving. Increasing complexity should be favoured if adding complexity enables more accurate results to be produced in terms of projections. Furthermore, modellers should be expected to be able to communicate complexity to the relevant stakeholders in an appropriate manner (see Section 6.4.). Simple models may be more appropriate for specific end-uses and are usually preferred when the goal is not to predict the future, but to comprehend the consequences of changes in policies. They provide a better understanding of the various effects, policy measures, for example, not only for policy makers but also for the modellers themselves.

The gains from complexity, whether by making some parameters endogenous, adding new variables or by using more disaggregated demand models, need to be assessed carefully and trade-offs between complexity and impact balanced. To inform work in this area, the next two sections provide a review of different scenario types and the relevant energy models.

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[15] See for instance Wilson and Dowlatabadi (2007) and Politt and Shaorshadze (2013).

[16] See Wilson, Pettifor and McCollum (2014).

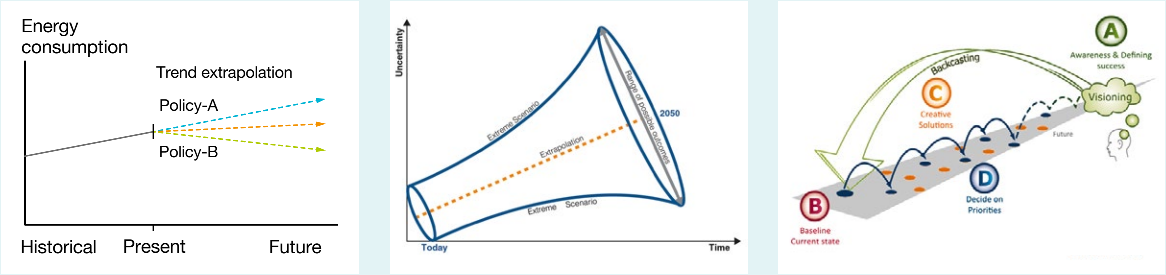
3.

BROAD SCENARIO CATEGORIES AND DEVELOPMENT APPROACHES

Scenarios are often categorised as qualitative versus quantitative, or exploratory versus normative. Qualitative scenarios describe plausible long-term futures and are based on the observations of multiple stakeholders. They are presented in the form of narratives or storylines, which need to be subjected to quantitative analysis to verify consistency. Following Börjeson et *al*. (2006) and Vergragt and Quist (2011), this section first describes three categories of scenarios, namely (i) forecast-based[17], (ii) exploratory and (iii) normative scenarios as they are used in the context of energy systems. Many of these scenarios are developed as either qualitative or quantitative scenarios or as hybrid scenarios, in which case attempts are made at bridging different scenarios.

These three types of scenarios form the fundamental basis for future studies, classified as *likely futures* in forecasting, *possible futures* in exploratory scenarios or *normative / desirable futures* in backcasting scenarios, (see Box 5). Both exploratory and backcasting scenarios were developed in the 1970s as alternatives to forecasting. As described in the following subsections, these scenarios are not used in the same manner by all institutions – a demonstration of distinct knowledge bases, organisational resources and analytical rigor. Section 3.1 is followed by a brief description of the base on which the scenarios are developed, focusing on a participatory approach.

Box 5: Different types of scenarios



a. Forecast-based scenarios

b. Exploratory scenarios

Source: WEC (2013)

c. Backcasting scenarios

Source: www.naturalstep.org

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[17] Börjeson et *al.* (2006) use the term “predictive scenarios” to include forecasting and what-if scenarios, while Vergragt and Quist (2011) distinguish between trend-extrapolating scenarios and classify forecasts under exploratory scenarios. Herein, forecasts are used as data-driven projections, encompassing both trend-extrapolations and what-if predictions.

3.1 Broad scenario categories

3.1.1
Forecast-based scenarios

Forecast-based scenarios are usually quantitative, empirical scenarios[18]. Different forecasting traditions either from a deterministic perspective or taking a positivistic (presupposition) stance – as in what-if scenarios – will project distinctive future paths. These are noticeable from the underlying assumptions of what is to happen. Deterministic forecasts are, by definition, point estimates. The simplest forecasts are based on simple trend-extrapolation as used for business-as-usual (BAU) scenarios or reference scenarios; they constitute a sub-class of forecast scenarios and only consider policies already in place (i.e. current policies), typically assuming linear effects over the forecast horizons. They indicate what is likely to happen if no further actions are taken, or if new policies fail. They are based on known data, i.e. historical knowledge obtained from the past. Box 6 summarises some of the major considerations when using deterministic forecasts.

Many forecasts also include new policies, whether already in place, or expected with a reasonable degree of certainty to be so, and are adjusted according to the expected impact of these policy interventions. However, the complexity of energy systems – in view of inter-market coupling – also makes it hard to predict policy impacts. *What-if* forecasts are based on different *what-if* scenarios of possible policy impacts, including potential breaks in trends and are often referred to as *projections*.

Organisations using forecast-based scenarios include the International Energy Association (IEA), the U.S. Energy Information Administration (EIA), BP and Statoil, but they differ in their forecasting approach. In particular, we can distinguish between aggregated forecasting approaches and bottom-up demand forecasting approaches. EIA's National Energy Modelling System (NEMS) is one such bottom-up forecasting and analytical tool that uses a four-fold segmentation (residential, transportation, industrial and commercial sectors[19]) of energy demand for each of the nine US census regions; demand is determined by market-clearing prices (prices at which demand and supply are balanced) in end-use demand regions. As discussed in Section 4, many scenarios are also based

Box 6: Major considerations for using deterministic forecasts

Deterministic forecasts are based on a number of building blocks, namely (i) discernible and quantifiable past trends; (ii) steady and persistent societal structure and social behaviour; and (iii) the assumption that underlying data is neutral and reproducible. These assumptions are necessarily violated in any system undergoing transition. To be useful, deterministic forecasts have to be reproducible and open to easy and objective validation, i.e. unencumbered by the subjective criteria or mental image of experts in model assessment. Robinson (1982) gives some examples of selection/perception bias including instances where lack of knowledge of new behaviours can lead forecasts astray.

Although well-specified econometric models can have reasonable short-term predictive power, by definition, long-term forecasts are highly uncertain. BAU forecasts, for instance, often overshoot; decisions based on excessive forecasts can have real (often negative) consequences. High demand growth projections may be used to justify investment in the construction of large energy plants, which leads to wasteful over-capacity that, in turn, may encourage over-consumption. It highlights the self-fulfilling potential of high predictions and potential technological lock-in considering the long lifetime of energy infrastructures.

Another problem with forecasts is that deterministic forecasts – in the form of point-estimates or those based on the "*most likely*" criterion – are the most commonly reported. The risk is that point-estimates provide a false-sense of confidence to decision-makers. Probabilistic forecasting (Morgan and Keith, 2008) and stochastic scenario analysis (Kann and Weyant, 2000; see also Section 5.2.2) are therefore recommended.

The usefulness of deterministic forecasts lies not in predicting the long to very long term, but in its ability to help verify the internal consistency of diverse projections of energy futures, especially those forecasts determined by complex and frequently, complex black-box models.

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[18] There is common confusion that demand forecasts are necessarily quantitative construct. However, some decision-makers may use qualitative demandw forecasts that are based on the intuition and judgment of experts, especially when trends are uncertain and data for quantitative analysis is inadequate or not available.

[19] www.eia.gov/forecasts/aeo/nems/documentation/integrating/pdf/m057%282013%29.pdf

on hybrid models that take into account both bottom-up and top-down modelling approaches. Statoil Energy Scenarios include *what-if* forecast scenarios, based on expert judgment of changes in trends, the precise timing of which is inevitably uncertain.

3.1.2
Exploratory scenarios

Exploratory or explorative scenarios look at alternative futures of the energy system and its subsystems, based on an understanding of the present and expectation as to what could happen should an event come about or a trend grow. Exploratory scenarios are *IF-THEN* scenarios and are often informed by wildcard[20] analysis. Organisations using exploratory scenarios typically focus on extreme scenarios that demonstrate polarities. This implicitly recognizes that the future is unforeseeable. In addition, extreme scenarios are not intended to be perceived as good or bad, but as plausible depending on the drivers of the underlying scenarios (see Box 7 for an illustration).

Organisations using explorative scenarios include Shell (2008, 2013), the World Energy Council (2013) and ExxonMobil (2013), all focusing on extreme scenarios or maximally contrasting scenarios, driven by opposing assumptions of the scenario drivers. For example, in the WEC-PSI Jazz Scenario, technologies are chosen by the market, while in the Symphony Scenario, it is governments that select the technology.

Box 7: WEC-PSI Jazz and Symphony Scenarios

Jazz	Symphony
Overview	
World where there is a consumer focus on achieving energy access, affordability, and quality of supply with the use of best available energy sources.	World where there is a voter consensus on driving environmental sustainability and energy security through corresponding practices and policies.
Many players are multi-national companies, banks, venture capitalists, and price-conscious consumers.	Main players are governments, public sector and private companies, NGOs, and environmentally minded voters.
Technologies are chosen in competitive markets	Governments pick technology winners
Energy sources compete on the basis of price and availability	Selected energy sources are subsidized and incentivised by governments
Renewable and low-carbon energy grows in line with market selection	Certain types of renewable and low-carbon energy are actively promoted by governments.
In the absence of international agreed commitments, carbon market grows more slowly from the bottom up based on regional, national and local initiatives.	Carbon market is top-down based on an international agreement, with commitments and allocations.
Consumer acceptance	
High public acceptance of energy infrastructure projects consistent with access to cheap and affordable energy sources	Tension between voter consensus on driving environmental sustainability through government decisions and individuals and NGO opposition to new developments, leading to fewer project developments and less infrastructure reinforcement.
Consumer behaviour and lifestyle	
Higher energy consumption irrespective of energy-efficiency savings; higher energy prices motivate more investments in efficient equipment, insulation and appliances (i.e. such investments are justified by efficiency gains and economics).	High impact from energy efficiency and saving programmes. Global demand for energy is lower because of lower growth and changes in lifestyle (i.e. heightened environmental consciousness), in part triggered by government incentives.

Source: Adapted from WEC-PSI (2013)

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[20] Wildcards refer to sudden or unique incidents that can constitute turning points in the evolution of a certain trend or systems; their anticipation depends on the foresight capabilities of the scenario builders.

3.1.3
Normative scenarios

Normative scenarios are based on visioning, often combined with backcasting[21]. In backcasting, the first step is to set the desirable end-state most often through a multi-stakeholder process that defines a desirable energy future – because of this visioning process backcasting scenarios are considered to be normative. Then, on the basis of the desirable future and assessment of trajectories or pathways that could have been taken given the current state, possible paths or roadmaps[22] to bridge the gap between the current state and envisioned end-state are developed. Normative scenarios can thus be seen as potentially more ambitious. Importantly, energy backcasting is closely policy-oriented and is particularly appropriate for the optimization of energy demand (Karjalainen et *al*., 2014). It is noteworthy that since its development in the 1970s, backcasting has, to a significant extent, evolved into a participatory exercise (see Section 3.2).

Organisations using backcasting philosophy include the IEA (450 ppm scenario), ENERDATA (Very Long Term Energy Environment Modelling, VLEEM[23]). The IEA World Energy Outlook 450 ppm scenario, for example, fixes the emissions target at 450 ppm and assesses the demand level and energy mix that would help achieve this target.

3.1.4
Hybrid scenarios

Many scenarios are either qualitative or quantitative in nature. In addition, except for backcasting scenarios, the end-points of the energy systems determined by other types of scenarios are uncertain. Because of this, and more generally, there are conceivable merits to integrating different types of scenarios.

Firstly, the combination of forecast-based and exploratory scenarios is necessary because while energy forecasts are subject to uncertainty, exploratory scenarios investigate the uncertainty and together they reveal important issues. They are particularly pertinent for short-term decision-making in view of the long-term objectives (O'Mahony, 2014; O'Mahony, Zhou and Sweeny, 2013).

Secondly, because exploratory scenarios are by and large qualitative scenarios that are often presented in the form of storyline scenarios, they have to be analysed with quantitative energy system modelling (i.e. it is important to quantify qualitative scenarios) so as to understand systemic effects. This is especially the case when these exploratory scenarios concern highly uncertain and complex sociotechnical contexts. Examples include the Story and Simulation (SAS) approach (Alcamo, 2001, 2008) used, for instance, in the IPCC Special Report on Emissions Scenarios (SRES)[24], and McDowall (2014) as well as sociotechnical scenarios (see Box 8).

Thirdly, the combination of backcasting and exploratory (and/or forecast-based) scenarios can be adopted as a means to develop robust strategies and policies (see, for example, van Vliet and Kok, 2013), where backcasts are positive performance metrics, such as sustainability elements, that are introduced as *constraints* in otherwise undesirable futures (such as excessive carbon emissions). The long horizon of energy backcasting has to be balanced with the short-term approach of forecasting used to inform policy (see Box 9 for a description of the IEA's integration of backcasting and forecasting).

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[21] As used in this document "backcasting" refers to choosing some desired future end-state and then asking what has to happen to result in that end-state. The term backcasting has a second meaning in which an existing model is initialized at some time in the past and then run forward to see how its outputs compare with what has actually happened. This approach is widely used in natural science, but unfortunately is rarely used in energy modelling.

[22] The WBSCD (2010) backcasts from a vision of a sustainable world and suggests nine pathways to the desired end-state.

[23] www.vleem.org/PDF/final-report.pdf

[24] See www.ipcc.ch/publications_and_data/ar4/wg2/en/ch2s2-4-5.html
and www.ipcc.ch/publications_and_data/ar4/wg2/en/ch2s2-4-6.html

Box 8: Sociotechnical Scenarios

Sociotechnical scenarios (STScs) are hybrid scenarios that combine normative and exploratory scenarios, and are informed by the critique that energy models (described below) poorly reflect social and political developments (Weimer-Jehle, Prehofer and Vögele, 2013). Revealingly, Nielsen and Karlsson (2007: 314) argue that “Energy scenario studies tend to leave out important descriptions of the total system they are part of (economic, social and infrastructural structures in society) leading to conclusions detached from the political context in which they act.”

Accordingly, STScs include strong societal and behavioural change to assist policy makers in designing strategies that take into account the long-term and socio-technical nature of transitions (Hofman et *al.*, 2004). The predominant premise of STScs is that system-wide innovation, involving changes in technologies, user practices, legislation, infrastructure, networks and institutions, results in much greater improvement than partial system redesign and system optimization (in decreasing order). For large-scale transitions involving technological change, STScs provide a viable alternative to the oft-used technological forecasting methods (typically based on technological substitutions) that are of limited value because they pay little or no attention to the interaction between technology and society. STScs have been informed by several lines of research on co-evolving sociotechnical system (e.g. Geels, 2002), techno-institutional complex (Unruh, 2000) and the perspective that technological systems are “both socially constructed and society shaping” (Hughes, 1987). The integration of *actor* and *technology* networks thus follows from the observation that economic agents have the ability to influence system outcomes through deliberate choices but that their influence is diminished by interactions with other actors (actor networks) and technologies (technology networks, Hughes and Strachan, 2010). The integration is based on co-evolution and feedback processes.

The main advantage of sociotechnical scenarios is that they are normatively guided explorations of the future. As such, they retain plausibility and improve policy relevance through attention to real-world constraints faced by actors and their agency as well as through feedback modelling. Actors in these scenarios can be divided into two categories, namely current and new. Current actor behaviour can be modelled on existing evidence, whether from historical analysis, interviews or expert surveys, while the behaviour of new actors needs to be hypothesized or inferred from role plays or new models. These scenarios also allow for changes in current actors’ motivations, distinguishing between intrinsic and extrinsic drivers, and the consequent changes in technical system dynamics (Hughes, Strachan and Gross, 2013).

In Europe, sociotechnical scenarios are used increasingly to inform the transition of energy systems, whether driven by national or regional policies such as the European Union’s Strategic Energy Technology Plan (SET-Plan[25]), and as reflected in the work of Ornetzeder, Rohracher and Wächter (2012), Foxon et *al*. (2009) and Helmholtz-Alliance Energy-Trans[26].

Box 9: Integration of Backcasting and Forecasting in IEA ETP Scenarios

Energy Technology Perspectives 2014 (ETP 2014) applies a combination of backcasting and forecasting over three scenarios from now until 2050.

Advantage of this approach: Backcasting lays out plausible pathways to a desired end-state. It makes it easier to identify milestones that need to be reached, or trends that need to change rapidly, for the end-goal to be achieved. In this case, the advantage of forecasting, where the end state is a result of the analysis, is that it takes better into account the short-term constraints. By combining differing modelling approaches that reflect the realities of the given sectors, together with extensive expert consultation, ETP obtains robust results and in-depth insights.

Weaknesses of the approach: The analysis and modelling aim to identify the most economical way for society to reach the desired outcome, but for a variety of reasons the scenario results do not necessarily reflect the least-cost ideal. Many subtleties cannot be captured in a cost optimisation framework: political preferences, feasible ramp-up rates, capital constraints and public acceptance. For the end-use sectors (buildings, transport and industry), doing a pure least-cost analysis is difficult and not always suitable. Long-term projections inevitably contain significant uncertainties, and many of the assumptions underlying the analysis are likely to prove to be inaccurate.

Source: Adapted from www.iea.org/etp/etpmodel

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[25] europa.eu/legislation_summaries/energy/european_energy_policy/l27079_en.htm

[26] See www.energy-trans.de/english

3.2 How scenarios are developed

Scenarios can be developed in many contrasting ways. They can be based on expert opinions as in the case of Shell scenarios, they can be elaborated through multistakeholder participatory approaches or they can be more desktop research-oriented, based on literature reviews and trend analyses that are then fed into a modelling framework. These different approaches can be used alone or in combination to develop energy scenarios. Herein, participatory scenarios are briefly described because, in the context of energy transitions and sustainable development, we observe today an increasing interest and value in involving relevant stakeholders at an early stage in decision-making.

Participatory scenarios result from a scenario development/elaboration approach that provides a platform for different actors – from industry, government and the public – to better understand the perspectives of other actors, thereby stimulating social learning and triggering systemic thinking. In particular, capacity is built for participants to contemplate diverse futures and associated socio-ecological challenges (Johnson et *al*., 2012) or socioeconomic challenges. Participatory scenarios thus serve to align visions among the diverse actors and *guarantee* their respective engagement to reach the agreed-upon vision.

The French National Energy Debate[27] illustrates the application of participatory scenarios through civil society engagement to inform the French Energy Transition. Notably, to inform the National Debate, quantitative and normative scenarios – obtained by coupling visions and analytical expertise and developed by different stakeholders and institutions (such as, ADEME, Agence Nationale de la Recherche, Union Française de l'Electricité, and Gaz Réseau Distribution France) – were analysed and discussed. The outcome of the National Debate has influenced the *Loi de programmation sur la transition énergétique* – the legal framework for the French Energy Transition.

While in the French National Debate, a set of already-quantified scenarios was brought to the participatory platform, it is also quite common to elaborate on qualitative scenarios on a participatory basis. For instance, Bibas et *al*. (2012) combined a participatory scenario with an energy system model (see Section 4) to assess economically feasible pathways to a low-carbon French economy. To improve the outcome of the participatory process, context visualization, visual analytics, and often role games are used. Such a participatory scenario process was applied to study the potential for further decentralization of the German energy infrastructure (Karger and Markewitz, 2011).

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[27] Report of the national council for the National Debate on the Energy Transition: "Quelle trajectoire pour atteindre le mix énergétique en 2050?," Maryse Arditi, 2013. See also, Bibas et *al*. (2012).

4.

MODELLING ENERGY DEMAND

Many scenarios are developed on the basis of outcomes of one or many energy models, or of different parameterisations for a single model. Alternatively, different qualitative scenarios are fed into energy models for quantification. Energy modelling has been used since the 1950s to analyse energy systems or subsystems to different ends such as to:

- Improve the understanding of current and future markets in terms of supply, demand and prices
- Facilitate better design of energy supply systems in the short, medium and long-term for given demand forecasts
- Ensure sustainable exploitation of scarce energy resources
- Assess the present and future interactions of the energy system and rest of the economy
- Assess the potential implications in terms of environmental quality
- Assess the environmental, energy and economic policy impact.

There are different types of energy models. These are broadly classified as top-down (macroeconomic), bottom-up (techno-economic or engineering) or hybrid (energy-economy) models. There are also methodological differences as to how these models are used to produce scenarios. In particular, models differ in their use of equilibrium (general or partial), optimization (minimize/maximize some objective function – cost, sustainability metrics, welfare, profits – under number of constraints), accounting models, and simulation methods (solve a set of equations, which are often specified to correspond to welfare maximisation). They are based on different theoretical or scientific foundations, namely engineering and social sciences, including economics (typically, neoclassical or new-Keynesian schools of thought even though behavioural economics is gaining traction; see Box 10). In some of these models, energy demand enters as an exogenous parameter. In others, an endogenous approach is taken.

Figure 4 illustrates a three dimensional representation of energy-economy models, as described below:

- An ideal model (top-right) will incorporate all relevant features from the three dimensions but there may be costs (computational and informational costs) associated with the development and quantification of such full-fledged flexible models.
- Conventional top-down models focus on macroeconomic completeness and, as will be discussed below, typically make simplistic (and, sometimes, unrealistic) assumptions about the microeconomic behaviour of agents.
- Conventional bottom-up models on the other hand often ignore the complexity/realism of microeconomic behaviour, focusing instead on technological explicitness.

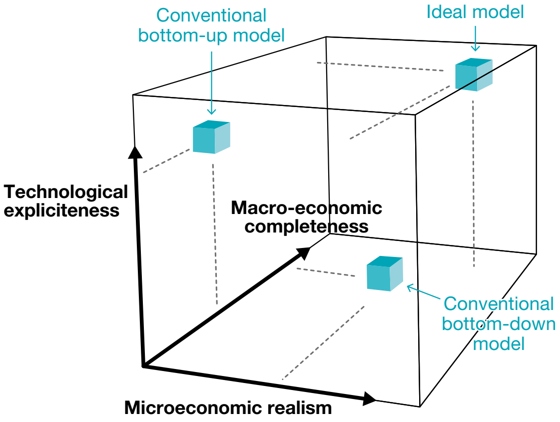

Figure 4: Hybrid modelling of energy-environment policies – reconciling bottom-up and top-down. *Source*: Adapted from Hourcade et *al.* (2006)

Box 10: Economic theories

Economic modelling approaches used in energy models are typically based on neoclassical theories or neo-Keynesian theories or a combination of both.

Neoclassical economics has influenced the modelling of microeconomic decisions for several decades. Neoclassical frameworks typically impose strong assumptions regarding optimizing behaviour – consumers maximise utility under budget constraints and firms maximise profits under cost constraints; competition in markets. Perfect competition implies that markets instantaneously clear (general equilibrium approach), implying full employment in the labour market and interest rates that balance household savings with capital demanded by firms for investment. It further assumes perfect foresight, and that consumer preferences are given. Energy models based on the neoclassical framework, by using different levels of demographic and sectoral disaggregation, allow for a diversity of behaviours, but still assume rational, optimising behaviours.

Neo-Keynesian models relax the assumption of instantaneous price adjustment and allow for slow-adjustment of effective quantities and their prices to their notional level, thus allowing for the existence of sub-optimal equilibria such as involuntary employment. Neo-Keynesian macroeconomic frameworks are in general aggregate models and typically do not distinguish between different types or energy carriers and end-uses. As a result they are not useful, unless linked to other (bottom-up, sectoral) models, for effective assessment of energy and environmental policy.

A third class of economic paradigm is **Behavioural Economics** that can be particularly informative for the analysis of energy demand, particularly in view of the impact of consumption behaviour on the effectiveness of energy efficiency and energy sufficiency policies. Behavioural economics purport that agents with similar economic characteristics can display different behaviours as a result of cognitive limitations, encompassing habit, as well as other behavioural factors such as greater aversion to losses than desire for same-sized games (as in Prospect Theory), preferences for immediate gratification (as in hyperbolic discounting or time-varying discount rates). These and other features such as an endowment effect (the extra value individuals attach to goods they already own or have already received), status-quo bias (the tendency for people to stick to the current option or default option offered to them), and pro-social behaviour (in particular, concerns for fairness) are not captured in the neo-classical framework, but are relevant for energy systems undergoing transformation.

Various attempts have been made to combine top-down and bottom-up models as in hybrid models. Section 4.1 provides an overview of different mainstream modelling approaches, revealing a dearth of microeconomic and behavioural realism. This is not a flaw in itself since various models have been developed for different uses and for specific contexts. Because energy transitions involve systemic effects at various levels, inaccurate representation of energy demand in models can lead to poor policy analysis and prescriptions. Section 4.2 describes mainstream integrated assessment models, which are often large-scale, long horizon models, allowing for environmental feedback on the energy-economy model. Section 4.3 highlights on-going work aimed at improving microeconomic models to provide a more realistic account of the behavioural aspects of energy-related decisions, encompassing psychological as well as lifestyle influences on energy decisions.

4.1 Mainstream Energy Modelling Approaches

4.1.1
Top-down modelling

Top-down models are macroeconomic models that represent energy use, technological change and the economy as a whole (i.e. at an aggregate level) focusing on macroeconomic effects and are based on *realistic* neo-classical representations of consumer behaviour and firm behaviour. While they lack detailed representation of technologies, they include feedback mechanisms to and from the energy systems, making them suitable for research on energy policy-making. But, some macroeconomic models such as NEMESIS (New Econometric Model Evaluation by Sector Interdependency and Supply[28]) explicitly model technological change as a result of investment in research.

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[28] www.ecmodels.eu/index_files/The NEMESIS Model.pdf

Computable General Equilibrium (CGE) models are a specific type of top-down model that focuses on multi-market equilibrium in an economy (e.g. GEM-E3[29]). Because CGE models capture, in a realistic manner, all economic transactions between the economic agents, they are particularly suitable for evaluating policy reforms and the choice of policy instruments, and for capturing the complex relationship among all sectors. Top-down models using econometric analysis, e.g. HERMES[30] and NEMESIS are more suited as projection tools. Another subclass of top-down models is the Input-Output model that sets up a mathematical model (based on a set of algebraic equations) to represent the structure of the national economic system and the social processes.

Demand in top-down models is derived endogenously. Typically, energy consumption is directly related to income through a nested utility function that is based on specific assumptions. For instance, the Dynamic Integrated Climate-Energy (DICE) model (Nordhaus, 1992) focuses on price-quantity relationships and feedback to the economy (equilibrium) with few demand and fuel categories. In GEM-E3, consumers and firms respectively maximize welfare and minimize costs. GEM-E3 uses the Stone-Geary Utility function, which implies that the demand function is such that expenditure is linear in price and income; and demand is sensitive to all prices. The model distinguishes between durable and consumable goods and services, where utility from a durable derives from using the durable good above a subsistence level. The main drawback of top-down models for demand anticipation is the highly aggregate nature of energy demand (and supply) specifications.

4.1.2
Bottom-up modelling

Bottom-up models are techno-economic models that have extensive technological details and typically conjecture a perfect substitution of old for new technologies and that society will always choose the least-cost technology option. These technical and behavioural shortcomings notwithstanding, bottom-up models do not include feedbacks from the economy as a whole, i.e. they are based on partial equilibrium analysis. This implies that macroeconomic effects of changes in prices and structural changes in the economy are not captured; instead the macroeconomic background remains exogenous. Partial equilibrium models are often perceived to be very effective for evaluating the impact of policies of which the effects are expected to be limited to specific sectors or markets. That said, large changes in a single sector might require general equilibrium analysis. As such, in most cases, partial equilibrium analysis is preferred to general equilibrium analysis when policy changes under study are expected to produce effects on the energy markets that are too small to justify the complexity of general equilibrium models.

Bottom-up models focus either on the supply-side and energy conversion to analyse the effect of introducing energy efficiency measures, e.g. Market Allocation Model (MARKAL[31]) and Energy Flow Optimisation Model (EFOM; Finon (1974)) or on the demand-side to analyse changes in energy demand and consumption as a result of changes in human activities. Models of energy demand are based on:

- Energy accounting approaches concerned with balancing energy demand and resources, e.g. Long-range Energy Alternative Planning (LEAP[32]), which is an econometric, terminal consumption model. LEAP can be used to design the energy consumption mode against various developments on the basis of: (a) the current energy demand of each sector and (b) the forecasts of social and economic development in future years based on different policy packages and technology selection modes. While it can be used for scenario analysis conditional on prior scenario development, LEAP cannot be used for optimization.

- Simulation approaches, e.g. the World Energy Model (WEM[33], used by IEA for the World Energy Outlook) that focuses on quantities simulation. In particular, the demand module is based on disaggregated end-uses where economic activity, energy prices and other variables are used for forecasting energy demand. Other examples include:

  (i) The IEA Energy Technology Perspectives (ETP), where the energy demand sector model is split into three sectorial models: transport (Mobility Model, MoMo), industry and building. These demand-side models are stock-accounting simulation models that allow for sectorial projections of energy use, emissions and costs until 2050.

  - ETP MoMo scenarios and projections are based on hypotheses about GDP and popula-

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[29] ec.europa.eu/jrc/en/gem-e3/model

[30] See EC (1993)

[31] A summary can be found at www.iea-etsap.org/web/Markal.asp

[32] www.energycommunity.org/documents/LEAPIntro.pdf

[33] www.iea.org/media/weowebsite/energymodel/WEM_Methodology_WEO2011.pdf

tion growth, travel demand, vehicle technology shares, fuel economy and costs. Fuel use is computed using the ASIF framework[34].

- Behavioural aspects (avoid/shift/improve) are integrated in the 2DS[35] passenger transport. The buildings model integrates end-use services such as space heating and cooling, lighting, residential cooking and appliances. The key variables of the model include GDP, population (urban vs. rural), share of flow area heated/cooled, appliance penetration rate and appliance unit-energy consumption.
- The industry model looks at low- and high-demand variants for material production, focusing on the five most energy-consuming sectors (iron and steel, cement, chemicals and petrochemicals, pulp and paper and aluminium).

(ii) The *Modèle d'Evolution de la Demande d'Energie* (MEDEE; Lapillone and Chateau (1981)) is another simulation model of energy consumption, designed for long-term energy demand evaluation based on scenarios that concern a country's social, economic and technological evolution. It is significant that the MEDEE family of models now includes MEDPRO, a model that puts emphasis on, among others, electricity load curves and greenhouse gases, making it useful to evaluate change induced by energy efficiency, energy substitutions and mitigation policies. MEDPRO provides perspectives on the consequences of social and technological evolutions for a country or region.

One important aspect of bottom-up models is their time and spatial resolution, enabling them to capture the impact of the renewable energy supply dynamics on energy demand. There is a risk in downplaying the importance of time and space resolution; poor spatiotemporal resolution, for instance, does not capture the need to integrate certain types of technologies like storage or demand-response or smart-charging of vehicles (Pina et *al*., 2013).

4.1.3

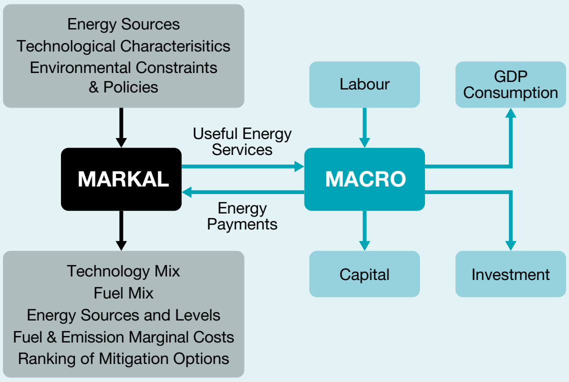
Hybrid modelling

Hybrid models aim at combining the technological explicitness of bottom-up models and the economic richness of top-down macroeconomic models. The two types of models can be combined through a soft- or hard-linking approach. Hard-linking implies that the bottom-up and top-down models are integrated into a single model, which by necessity, is simplified for optimisation. Soft-linking means that the models are linked through an iterative process; the respective models are aligned when certain key parameters, e.g. prices and quantities, converge. Such convergence may not be easy to achieve. MARKAL Macro[36] is an example of a hybrid model that has been developed to facilitate direct calculation of macroeconomic impacts due to changes in the energy sector as well as endogenous behavioural change in energy service demands. MARKAL family models, including MARKAL Macro have been extensively used to inform the energy reforms in the United Kingdom

Box 11: Markal-Macro Model

Markal-Macro provides an integrated economic analysis by combining the detailed bottom-up MARKAL model with a simple economic growth model. Key advantages are:

- **Firstly**, it allows for demand feedbacks from changes in energy prices captured through price elasticities and sector-specific costs of altering demand for energy services.
- **Secondly**, it accommodates autonomous demand changes that make the Markal-Macro model useful for scenario analysis where energy demands are decoupled from economic growth.
- **Thirdly**, demand-side behavioural response can be factored in.



Source: Adapted from Strachan, Kannan and Pye (2007)

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[34] Activity (passenger travel) x Structure (travel by mode, load factors) x Energy Intensity = Fuel Use.

[35] 2DS is a vision of a sustainable energy system of reduced Greenhouse Gas (GHG) and CO_2 emissions.

[36] www.psi.org.uk/site/project_detail/967

4.2 Integrated Assessment Models

Primarily developed for the purpose of climate modelling, Integrated Assessment Models (IAMs) combine the socioeconomic and scientific aspects of climate change with the intent of assessing policy goals (see Box 12 for an overview). IAMs have traditionally been classified as either top-down or bottom-up models, but increasingly are being developed as hybrid models, combining the macroeconomic consistency of top-down models with the technological resolution of bottom-up models (Krey, 2014).

Models include DICE (see 4.1.1), which has been criticized for its extreme sensitivity to initial assumptions and choice of discount rates, or the Regional Integrated Model of Climate and Economy (RICE[37]), which is a first attempt at disaggregating IAMs at regional level.

Attempts are also being made at nesting demand in IAMs. For example, for the purpose of estimating long-term energy demand in the building sector in India, Chaturvedi et *al*., (2014) use an IAM to estimate demand, with a view to discussing the implication of the booming building industry for Indian energy policy.

4.3 Improving the behavioural foundations of energy models

Conventional top-down and bottom-up models do not adequately capture complex and technological dynamics of end-use sectors in terms of end-use behaviour. There is a need for models that reflect behavioural realism. The EIA and IIASA[40] have been investigating the potential need for integrating insights from behavioural economics to improve the representation of consumer behaviour in NEMS and IAMs, respectively, in order to enhance the quality of energy demand analysis.

Both studies begin by expanding on the reasons for applying behavioural economics to energy demand mod-

Box 12: Overview of Integrated Assessment Models

IAMs fall into two broad classes: policy optimization and policy evaluation models.
Policy optimization models can be divided into three principal types:

- cost-benefit models, which attempt to balance the costs and benefits of climate policies
- target-based models, which optimize responses for given targets of emission or climate change impacts
- uncertainty-based models, which deal with decision-making under conditions of uncertainty.

Policy evaluation models include:

- deterministic projection models, in which each input and output takes on a single value
- stochastic projection models, in which at least some inputs and outputs take on a range of values.[38]

Current integrated assessment research uses one or more of the following methods (Rotmans and Dowlatabadi, 1998):

- computer-aided IAMs to analyse the behaviour of complex systems
- simulation gaming in which complex systems are represented by simpler ones with relevant behavioural similarity
- scenarios as tools to explore a variety of possible images of the future
- qualitative integrated assessments based on a limited, heterogeneous data set, without the use of models.[39]

IAMs have contributed to the establishment of important new insights to the policy debate, in particular regarding the evaluation of policies and responses, structuring knowledge, and prioritizing uncertainties. They have also contributed to basic knowledge about the climate system as a whole. Nonetheless, IAMs face two challenges, namely managing their relationship with research and disciplinary knowledge, and managing their relationship with other assessment processes and to policymaking.

Source: Adapted from www.ipcc.ch/ipccreports/tar/wg3/311.htm

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[37] See Nordhaus (2011).

[38] To be precise, stochastic projection models include not simply a range of values but some probabilistic description of values within the range. Deterministic analysis, on the other hand, can accommodate a range of values for an input through sensitivity analysis.

[39] Qualitative IAMs are developed when IAMS explore the climate change impact of future socioeconomic changes, many of which are not amenable to quantification. This approach was used by the IPCC as part of its 5th Assessment Report.

[40] See Wilson, Pettifor and McCollum (2014).

Box 13: Overview of the BLUE, Res-IRF and CIMS models

The BLUE model is based on probabilistic systems dynamic simulation and explores the interactions of different actors, the emergence of regimes and niches and associated uncertainties. Though dynamic, the model is myopic, that is actors make decisions assuming that current conditions will persist but they exhibit adaptive behaviour. The focus is on the electricity market and studies the impact of different behavioural parameters (market heterogeneity, defined as sensitivity to cost differentials in the uptake of new technologies; intangible costs and benefits; hurdle rates, which reflect diverse sensitivity to upfront capital investment; retrofitting/replacement rate; and demand elasticities) on the least-cost electricity solution.*

The **Res-IRF** model is "a bottom-up module of energy consumption for space heating, [that] has several distinctive features: (i) a clear separation between energy efficiency, i.e. investment in energy efficient technologies, and sufficiency, i.e. changes in the utilization of energy-consuming durables which allows the rebound effect to be assessed; (ii) the inclusion of barriers to energy efficiency in the form of intangible costs, consumer heterogeneity parameters and the learning-by-doing process; (iii) an endogenous determination of retrofitting which represents trade-offs between retrofit quantity and quality. The model is designed to assess and compare energy efficiency policies with a range of instruments (standards, carbon prices, subsidies, etc.)." **

In **CIMS**, a hybrid model, different behavioural parameters are used to more realistically represent consumer preferences for technologies. They include discount rate, representing time-value preferences; heterogeneity, accounting for the fact that different consumers have distinctive preferences for various technologies and therefore different valuations of their costs and benefits; and intangible costs, which represent non-financial costs associated with specific technologies (for example, greater risk associated with new technologies or different payback periods, to the extent they cannot be quantified due to lack of knowledge).***

* www.ucl.ac.uk/energy-models/models/blue

** www.imaclim.centre-cired.fr/spip.php?rubrique87&lang=en
See also rp.urbanisme.equipement.gouv.fr/puca/activites/prebat_220612/CIRED.pdf

*** Navius Research (2012). See also rem-main.rem.sfu.ca/theses/BeuginDale_2007_MRM443.pdf

elling. Regarding IAMs, Wilson, Pettifor and McCollum (2014) first observe that there is empirical evidence to suggest that many features cannot be explained through unbounded rationality or the neoclassical assumption of IAMs. Secondly, social sciences emphasize that end-user behaviour is driven by factors other than costs and prices. Thirdly, models with limited behavioural realism are not sufficient for evaluating *inter alia* energy-efficiency and climate-change mitigation policies.

EIA (2014) provides complementary rationale for turning to behavioural sciences: (i) energy consumption in homes and households with similar characteristics can vary widely; (ii) there are widespread and consistent disconnects between attitude and behaviours with respect to the environmental impact of energy consumption and awareness of energy conservation; (iii) adjustments to energy efficiency policies and programmes are necessary and should take into account individual decision-making biases; (iv) neighbourhood ranking of energy consumption leads to a sustainable reduction in energy consumption; and (v) pro-energy efficiency consumers are free-riding on subsidies for hybrid automobiles and solar panels.

The perceived policy-relevance of models with added behavioural features seems to provide a strong impetus for both research and applied work in this area. But, to date, there are very few behavioural models (see Box 13) namely, (i) Behaviour Lifestyles and Uncertainty Energy Model (BLUE) developed at UCL (UK), Consolidated Impacts Modelling System (CIMS[41]) developed by Canadian researchers and the French Residential module of Imaclim-R France (Res-IRF) model on the savings potential of the French residential sector (Strachan and Warren, 2011).

These few existing behavioural models relax rationality assumptions and attempt to represent different forms of market barriers and failures through parameters such as the discount rate (to capture time preference, option value and risk premium), market heterogeneity parameters (to account for different preferences across consumers and businesses), variables to capture hidden costs (intangible

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[41] CIMS belong to the class of IAMS, and is the only IAM that is not based on the assumption of a representative agent, whose behaviour can be represented by utility-maximisation (or even, price responsiveness) under income constraints.

costs, that may be modulated by a temporal parameter to capture information externalities) and innovation externalities (e.g. with learning-by-doing functions[42])[43]. Many of these parameters and newly incorporated variables are parameterized according to expert elicitation; more objective parameterizations are needed.

Both the EIA (2014) and Wilson, Pettifor and McCollum (2014) start out by identifying and then prioritising behavioural factors that could both significantly impact demand and have policy implications. The prioritisation is based on the strength of the evidence base (including the extent to which there is consensus about the directionality of influence of the behavioural factor); the impact on model analysis, including links to policy levers; and the ease of implementation in IAMs and NEMS modelling structures.[44] These studies highlight the need for a better evidence base. Moreover, the purported policy relevance of these behavioural models also suggests that research is needed to understand why social practices change and how they impact energy demand.

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[42] Most energy models include exogenous or autonomous technological change through autonomous energy efficiency improvement. Many models also account for endogenous or induced technological change – as a result of learning by doing – by means of technological learning curves, but do so in a rather indiscriminate way. The present Concept Note does not address this topic in detail. It is only highlighted that particular attention should be paid to the mechanisms that drive learning-by-doing in the model. These depend, among others, on model structure (e.g. top-down or bottom-up models and assumptions about expectations/foresight (discussed in Section 5.1.1).

[43] Wilson, Pettifor and McCollum (2014) explore how some of the above factors are likely to impact the adoption of alternative fuel vehicles.

[44] A number of behavioural factors and behavioural rules can be easily incorporated in NEMS owing to its modular and highly segmented structure. As for IAMs, Wilson, Pettifor and McCollum (2014) report that MESSAGE can accommodate some of the behavioural features in the buildings and transportation sector, but that more work is needed to extend such analysis to other IAMs.

5.

DIFFERENT FACETS OF DEMAND-SIDE UNCERTAINTY

Many uncertainties in energy systems are irreducible because some developments within the energy system are unforeseeable. As a result, long-term energy forecasts are almost always wrong and sometimes even wildly mistaken (as discussed in Section 2). It is therefore dangerous for policymakers to over-rely on them (Yetiv and Field, 2013). More sophisticated forecast models are not necessarily a *panacea* as "attempting to improve the quality of forecasting by increasing the sophistication of analysis is a bit like adding new wings to your car because it wouldn't fly with the first pair: the fault lies not with the accessories but with the vehicle itself" (Robinson, 1982). As such, forecasts may be more suited for short-term planning and other scenarios for long-term planning.

For long-term planning, there are some issues – technical, economic, political and social – about what knowledge can be built and incorporated into formal models, often at minimal cost of model complexity but with substantial gains in terms of policy or strategy relevance and usefulness. For instance, the sensitivity of model outcomes and policy prescriptions to discount rates needs to be better understood at both a strategic and policy level. Model uncertainty about physical and socioeconomic processes, encompassing consumer attitudes and business models, should be more thoroughly addressed. Likewise, the extent to which regulatory frameworks need to change should be factored into the analysis (UK ERC, 2014; Kann and Weyant, 2000).

5.1 Improving demand-side realism in energy models

In energy models, in particular bottom-up models, the supply-side of the energy system is characterized quite extensively. Demand-side, on the other hand, is represented by means of conventional demand functions and energy intensities while behavioural changes, whether due to changes in attitudes (e.g. driving less) or structural changes (e.g. the rise of sharing economy) or technological changes (e.g. energy efficiency), are either lumped together or represented in conventional ways according to end-uses. When planning for transitions that span several decades, these approaches have serious limitations because they do not allow new behavioural patterns to unfold/emerge. They can also be addressed by exploratory scenarios and fed into existing models.

There are also different views as to how to handle demand-side dynamics and associated uncertainties. Consider the rebound effect. Some argue that it should be explicitly incorporated into energy models, whether rebound effect is computed in terms of the energy-efficiency gap or emissions.[45] Others argue that "to the extent that rebound is fully captured through estimates of elasticities, partial and general equilibrium models include rebound by definition. The same is true for a number of

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[45] See Jaffe and Stavins (1994).

other integrated assessment models. For example, rebound effects can be explored by modifying a parameter in the MARKAL/TIMES family or models" (IRGC, 2013).

Energy efficiency is also linked to adoption and better use of energy-efficient appliances and therefore technology adoption should be modelled from the perspective of demand for end-use appliances and their usage (Wilson and Grübler, 2011). Wilson and Grübler's work indicates that there are behavioural lessons that can be learned from history, which are still relevant for current transitions. This section therefore explores some critical behavioural uncertainties that need to be better addressed in energy scenarios and, as appropriate, the models underlying them.

5.1.1
Time horizons and expectations

Many models are optimized under assumptions of rational expectations, perfect foresight (Muth, 1961), or myopic expectations. Sequential optimization is also common. The way expectations are formulated in energy models can have a significant impact on the outcome of interests such as investment in energy efficiency and demand elasticities. Perfect foresight assumes that the models are correct and that errors are random. In it, the modeller defines all the conditions determining prices, efficiency technologies and other relevant variables, and decisions (e.g. investment decisions by households and firms) are determined for the entire scenario horizon. Perfect foresight works well when the environment is stable and not susceptible to external shocks. Perfect foresight expectation is used in TIMES[46], a bottom-up model developed at IEA for exploring least-cost and long-term strategies in the energy sector, whether at a country or regional level; a stochastic version of TIMES includes the cost of uncertainty and a real options theory (see section 5.4.2).

Myopic expectations assume that the current system structure will not change dramatically over the planning horizon. Used in PRIMES[47] for some sectors – and used in the development of the European Commission's Energy Roadmaps 2030 and 2050 – and GEM-E3, the evaluation of an investment is based on current prices and current activity. Myopic models are thus relevant for short-term decision-making (see Box 14) under the assumption of no structural changes to the energy system.

How expectation (perfect or myopic foresight) is modelled affects how well the model can account for endogenous preference formation and structural changes in preferences. But this is an area that has received little attention either in literature or in practice. That said, there is an emerging approach that assumes neither perfect foresight nor myopic expectation. It is based on System Dynamics and agent-based modelling where agents (consumers and firms) use heuristic forecasting approaches for prices and other relevant variables when deciding on investments. The TIMER model is based on this approach (de Vries, et *al*., 2001). TIMER has been developed to analyse the long-term dynamics of energy conservation and the transition to non-fossil fuels – where fuel and technological substitution processes are driven by prices – and understand the long-term trends for energy-related greenhouse gas emissions. See Box 15 for a description of the TIMER Energy Demand module.

Box 14: Myopic models for assessing the impact of short-term decisions

Myopic MESSAGE is a model to analyse near-term policies and their consequences for long-term objectives and is a myopic or *limited foresight* version of the long-term energy system model MESSAGE, developed to better understand the implications for energy system evolution under the conditions of short-term decision making. In contrast to the traditional systems engineering and macroeconomic energy models with perfect foresight, the myopic model allows analysis of the implications of alternative planning horizons for decision making. It provides a suitable framework for exploring *path-dependency* and *lock-in-effects* in the energy system. In particular, the framework is used for the explicit assessment of the consequences of short-term decisions for achieving long-term objectives.

Source: www.iiasa.ac.at/web/home/research/modelsData/MESSAGE/MYOPIC-MESSAGE.en.html

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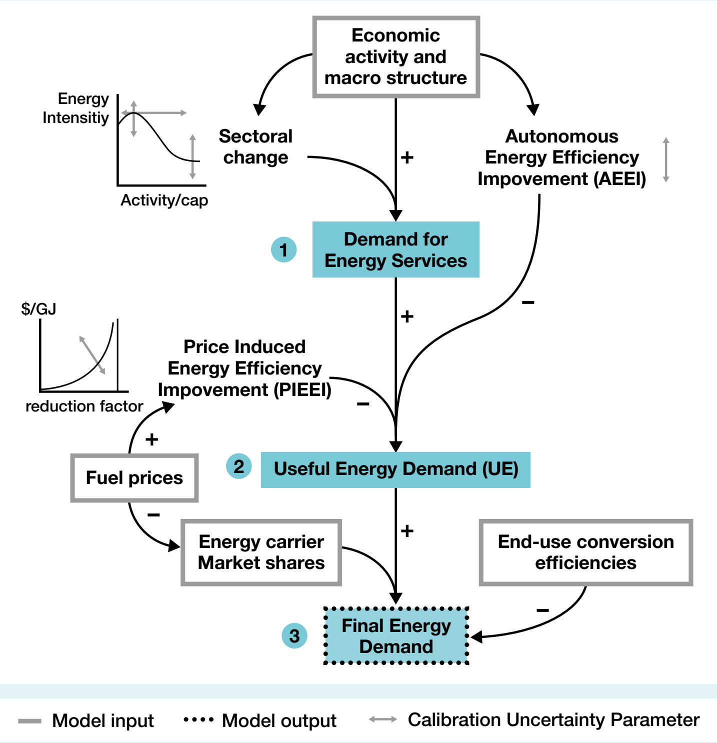
[46] www.iea-etsap.org/web/Times.asp

[47] www.e3mlab.ntua.gr/e3mlab/PRIMES Manual/The PRIMES MODEL 2013-2014.pdf

Box 15: Demand determination in TIMER model



Demand for final energy is modelled as a function of a variety of factors, following the structure shown on in the diagram.

① **Demand for energy services by sector** is determined by population, economic output and structure, corrected for energy intensity that varies across sectors and with the per capita activity level.

② **Useful energy demand** is obtained by first multiplying ① with progress-induced energy efficiency (AEEI) and then with price-induced energy efficiency (PIEEI) that reflects, inter alia, the effect of rising energy costs for consumers.

③ **Final energy demand** is determined by the conversion rate from final energy to useful energy and also by the relative prices of energy carriers, preferences, environmental policies and other strategic considerations.

Source: Figure adapted from van Ruijven et *al*. (2010); Text based on de Vries et *al*. (2001)

5.1.2
Human behaviour and social preferences

Human behaviour and social preferences, encompassing institutional and jurisdictional frameworks, supply-chain bottlenecks, and social barriers such as *Not In My Back Yard* (NIMBY) and *Build Absolutely Nothing Anywhere Near Anyone* (BANANA) attitudes and so-called *dragons of inaction*[48] can be important factors that influence the scope for converging to equilibrium points (defined as, for example, least-cost energy models) on the one hand, and influencing the outcomes of public and policy debates on the other hand. The UK ERC (2014) has stipulated that in view of systemic uncertainties related to the role of public attitudes "[…], there is a need to move beyond narrow framings of public attitudes […]" and the importance of "[…] engaging with the public in the kind of energy system they would like to see" rather than "persuading the public to accept a given set of technologies."

It follows that policies and choices that ignore behavioural change or structural changes in preference are bound to fail or be totally counterproductive. In this respect, it is often assumed that incumbents will necessarily resist change and raise artificial barriers to stall the emergence of new technological niches. Acknowledging that incumbents may seek to defend their market positioning through adaptation and understanding how, can help shed new light on the likely evolution of energy demand, and could be informed by agent-based modelling.

Other challenges related to the interrelationship between technological changes and social behaviour at individual, group and macroeconomic levels should also be addressed. For example, demand response associated with smart grid deployment, including firm-household interaction needs to be understood: the development of intra-day energy markets can raise feasibility issues with respect to supply-demand balancing of the electricity network. Dedicated electricity market models using agent-based analysis can be useful (Jackson, 2010).

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[48] Following Gifford (2011), dragons of inaction include limited cognition, ideologies, comparisons with others, sunken costs, discordance, perceived risks, and limited behaviour (i.e. adopting behaviours that are easy to implement (low-hanging fruit) but necessarily the most beneficial possible action).

It would be particularly interesting to identify socioeconomic and technological response strategies to energy challenges. Modelling frameworks such as MESSAGE developed at IIASA and used for IPCC reports and IIASA GEA reports can be developed to that end.

5.1.3
Time discounting and time preference

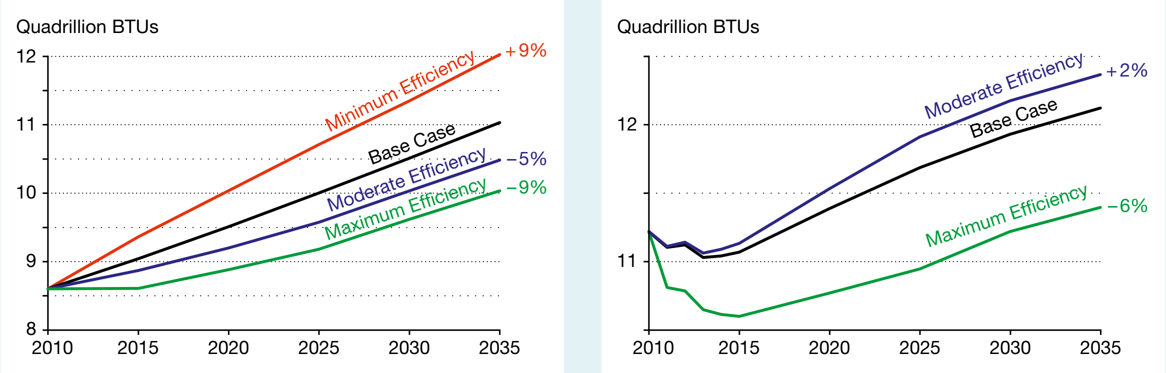
Discount rates help assess temporal trade-offs between the short-term and the long-term. A high discount rate places a strong preference for present-oriented actions. Different types of discount rates used in energy modelling are: the social discount rate, economic or market rate, hurdle rate, and individual or private discount rates[49]. Model outcomes are not invariant to the chosen discount rate (Wilkerson et *al*., 2013). Many models intended for policy analysis use social discount rates[50], but these ignore heterogeneity in the time preference of individuals.

The choice of an appropriate discount rate (e.g. social vs. private discount rate[51]) is important to avoid ex-post policy regret (Long, Zerbe and Davis, 2012) while understanding which discount rates have been used across different analyses can help resolve disagreements on energy-related policies (Goulder and Williams III, 2012). Declining social discount rates have been proposed in literature because of uncertainty (Weitzman, 2001) and heterogeneity in the time preference of individuals (Gollier and Zeckhauser, 2005). However, there is some controversy about time-declining social discount rates. Viscusi (2007), for instance, provides powerful analytic arguments that declining social discount rates produce clear irrationalities in decision making, such as the possibility of policy choice reversal, depending on when the decision is taken.

Wilkerson et *al*. (2013) study the sensitivity of scenarios to discount rates, focusing on end-use technology choice in the commercial and residential sector in the EIA's NEMS and highlighting that high discount rates is associated with minimum efficiency (see Box 16). Their analysis also reveals other factors that influence efficient technology uptake and, by extension, energy demand. So, depending on the sensitivity of energy demand to discount rates, quite large variations can be obtained for small changes in discount rates.

There is significant uncertainty as to the level of discount rates that should be used. This is particular true for emerging technologies such as low-carbon technologies.

Box 16: Sensitivity of final energy demand to discount rate



The figures show the final energy demand in the commercial (left) and residential (right) sectors for different efficiency scenarios, where the different efficiency levels are associated with different discount rates, e.g. 0% for maximum efficiency and 20% for moderate efficiency.

Source: Wilkerson et *al*. (2013)

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[49] Private discount rates depend on such assumptions as technological readiness/technology maturity: when consumers and suppliers are hesitant to adopt new technologies, a high subjective discount rate is generally imputed. But this may ignore feedback effects of technology deployment and policy on consumer perception. In general, it is also not clear whether consumers correctly discount the future (Hassett and Metcalf, 1993).

[50] This even if most energy models assume that energy demand and supply are based on price-driven interactions in markets. The discount rates of the interacting agents are not homogeneous: firms use weighted average cost of capital and individuals use subjective discount rates.

[51] See also IEA (2009).

In general, discount rates depend on technology maturity and policy risk, market arrangements and prices, systematic risks and idiosyncratic risks. Different discount rates can be obtained depending on, for example, the treatment of different types of risks (Lind et *al*., 1982). Considered together, these suggest that the quality and reliability of energy demand assessment can possibly be improved through a more rigorous choice of discount rates. But there are technical challenges too. Hyperbolic discounting as informed by behavioural economics, for instance, may make equilibrium models intractable.

5.1.4
Welfare and scaling issues in end-use energy demand

Welfare considerations are central to policy and are a natural concern of energy demand scenarios/models. Many models use aggregate behaviour or sectoral segmentation (typically industry, buildings and transportation). As such, they focus on either macro or meso-level behaviour. Models that break down energy demand from an energy services standpoint (e.g. passenger and freight transport, communication and lighting) and in terms of end-uses (e.g. food, entertainment, heating and cooling, etc.) are typically bottom-up models that are not concerned with welfare maximization. So, there are limits to using macro and meso-level models to assess whether transition goals are consistent with preservation or Pareto improvements in lifestyles.

To assess the *feasibility of transition targets* (such as reduction of energy demand by 30-40% to achieve the UK's target of reducing GHG emissions by at least 80% by 2050 as compared to 1990 levels), complex interactions among sectors need to be modelled using system dynamics approaches as in Prospective Outlook on Long-term Energy Systems (POLES) models (LEPII-EPE, 2009). To assess the *welfare implications of reductions in energy demand*, one needs to understand the drivers and impact of reduced energy demand on different segments of society. If demand is lower because end-use energy prices are too high, it may well be the case that a significant fraction of the population is worse-off. If lower demand is achieved through household investment in energy efficiency (e.g. retrofitting) at the expense of consumption of other welfare-improving goods and services, energy transitions may lead to welfare losses.

In this view, welfare assessment should not be an outcome of scenario analysis; instead Pareto-efficiency should be a normative goal along the transition and therefore included in the model. This can be facilitated by backcasting scenarios (van Vliet and Kok, 2013). Roadmapping[52] can be informed by behavioural models, which help understand socio-technical transition pathways and assess policy implications at micro-levels, for instance, by taking into account rural-urban differences, the size of households, income distribution. Top-down models that rely on household welfare maximisation and firm-level least cost optimisation assume purely utilitarian preference functions based on consumption and profits and rational behaviour driven by prices and may fail to comprehensively capture the welfare impact of transitions.

5.1.5
Structural uncertainty

The interdependent nature of uncertainties faced by governments, industry, citizens and communities are not captured well by energy models, which are not only largely simplified because of computational constraints[53] but are also uncertain. Structural or model uncertainty arises when there exists more than one plausible model structure (Morgan and Henrion, 1990). Moreover, different models place different value judgments on the evolution of drivers, which results in model biases such as path-dependence and non-ergodicity.

In common parlance, a system is ergodic if there is no path-dependence in its evolution; the system is therefore unaffected by the initial conditions. Such temporal ergodicity requires weak interactions for the system to settle down. But large-scale transitions are often characterized by strong interactions. Breakdown of ergodicity involves the notion of memory, i.e. history matters, giving rise to path dependence.

Path-dependence, in the form of adjustments lags, can also be a feature of model structure and can result in poor forecasts. Figure 5 shows the forecast of coal prices by the EIA from 1952-2005, indicating very slow adjustment to new lower prices and that forecasts were persistently above actual or realized coal prices. It is therefore important to identify path-dependent features in energy models to the extent that they influence energy demand, and use or develop appropriate approaches to address them.

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[52] See for example WBCSD (2010)

[53] Otherwise, models are quantified using reductionist methods.

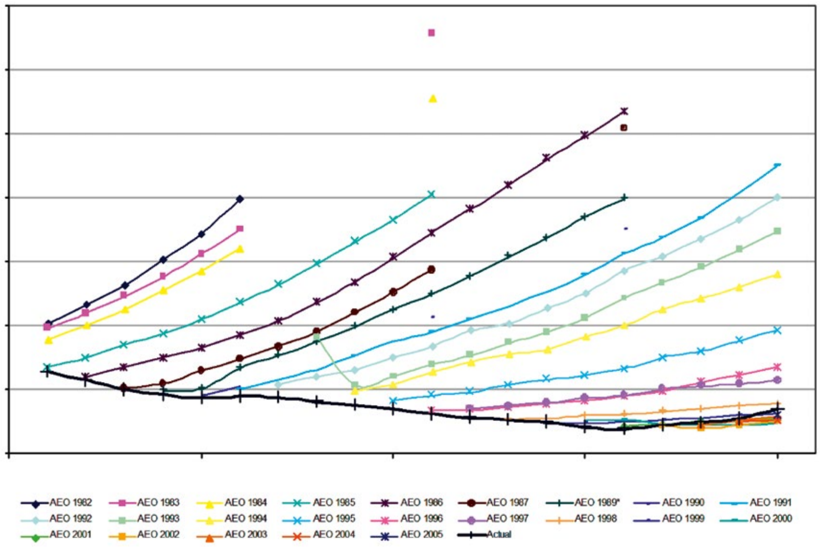

Figure 5: Adjustment lags in coal prices.
Source: Newcomer (2007) in www.irgc.org/wp-content/uploads/2013/02/3.-Granger-MORGAN_The-forecasting-problem_IRGC-Beijing-2013.pdf

Spatial ergodicity means that the dynamics on the level of aggregate behaviour is deterministic, akin to the existence of a representative agent. The assumption of ergodic spatial relationships may explain why scenarios are wrong. An appropriate level of disaggregation may give better insights. Analysis of the EIA's NEMS highlights the importance of segmentation and different behavioural rules across these segments (Kann and Weyant, 2000). Although the NEMS approach is not free from shortcomings, it suggests that the influence of behavioural heterogeneity on demand dynamics needs to be addressed in energy models.

5.1.6
Energy demand elasticities

Energy demand elasticities are a convenient way to summarize the responsiveness of energy demand to such factors as energy prices, income, prices of related goods and other relevant variables. Energy models have different levels of demand of aggregation, both across and within sectors. Demand elasticities are also determined for different energy carriers, e.g. for electricity, oil and natural gas. A substantial amount of work goes into estimating these demand elasticities. But often, once the elasticities have been estimated, they are assumed to be constant in energy models. There may be a caveat in energy analysis if elasticities are assumed to be constant but are, in fact, not, i.e. if they are time-varying.[54]

A recent study estimated the income and price elasticities of demand for domestic heating, passenger transport, and lighting in the United Kingdom over the 200-year period from 1800-2010 (Fouquet, 2014). The analysis showed that income elasticities for energy services rose in the early stages of economic development and then declined, but stayed positive throughout the entire period. While income elasticities can be represented by an inverse U-shaped curve, price elasticities followed a U-shaped curve but stayed negative, i.e. a rise in price leads a decrease in consumption, and vice versa (see Box 17).

These temporal dynamics in elasticities lead Fouquet to suggest that the decline in energy consumption that would be needed in the most optimistic climate change scenarios, is unrealistic. However, demand for energy services also evolves as a result of economic development and other economic, technological, political, social and cultural factors that are not captured in income and price elasticities. And, in many countries in the world, energy transitions are largely driven by environmental and political considerations.

What does this suggest for how energy demand, in particular demand for fossil fuel, might respond to the significant drop in oil prices that began in June 2014? Views may differ on this topic but, should the drop persist, fossil energy consumption need not necessarily rise. Investments in renewable energy may continue and the drop in oil prices provides a window of opportunity for governments across the world to cut down subsidies that have, for a long time, distorted prices of fossil-fuel energy (The Economist, 2015). Insights should also be sought regarding the time-varying cross-price elasticities of between fuels in different end-use sectors.

What are the implications of adding behavioural realism to energy models? Laitner et *al*. (2000) highlighted that short-term behavioural improvements to energy demand modelling could be achieved *inter alia* by using non-constant price and income elasticities. EIA (2014) further recognises that income elasticities may

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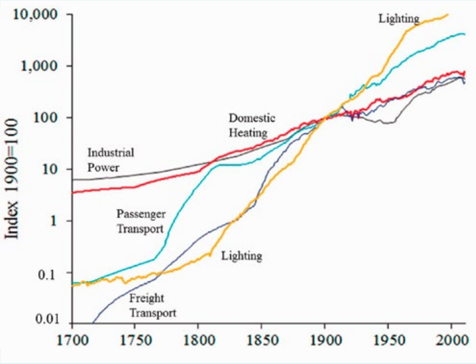
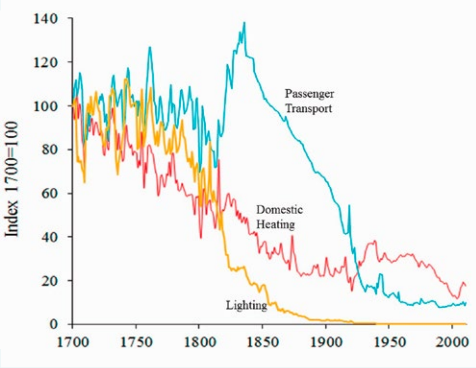
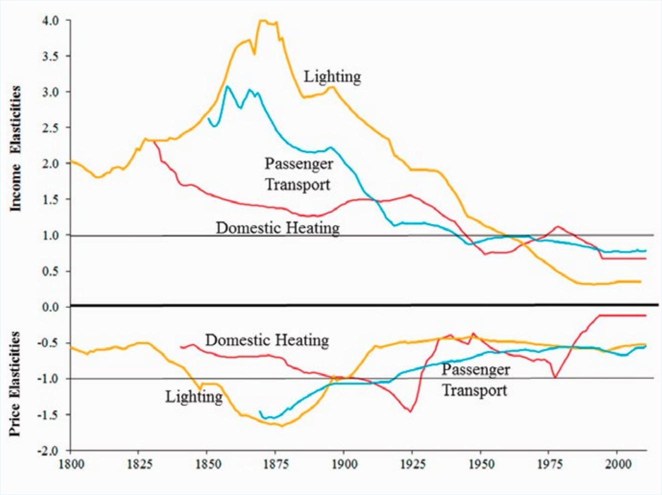
[54] The notion of time-varying demand elasticities is not new. See Fouquet (2014) and references therein regarding both the use of single and constant estimates, and other attempts at estimating changes in elasticities.

Box 17: Time-varying income and price elasticities of energy demand: the case of UK 1800 - 2000







Left (top): Consumption of energy services in the UK (Index 1900 = 100), 1700 - 2010.

Left (bottom): Price of consumer energy services in the UK (Index 1700 = 100), 1700 - 2010.

Right: Income and price elasticities of demand for energy services, 1800 - 2010.

Source: Adapted from Fouquet (2014), © Oxford University Press

vary across income segments and that the effect may be nuanced by pro-environmental behaviour. This suggests that lifestyle changes that may accompany and / or drive energy transitions may lead to changes in income and price elasticities. These changes must be tracked to reduce systemic biases in energy demand models, as when demand elasticities have a significant impact on model analysis.

5.2 Dealing with uncertainty: Some technical approaches

Uncertainty, to the extent that it is reducible or relevant for decision-making purposes, can be dealt with in many ways. Epistemological uncertainty can be reduced. Qualitative information can be processed using the best available methods. Scenarios can be combined according to the goals of scenario development to ensure internal consistency. And models, fit for purpose, can be simulated for different input parameters, and outcomes compared (sensitivity analysis) and contrasted with the outcomes of other models. Kann and Weyant (2000) document several approaches to dealing with uncertainty including scenario analysis (akin to the stochastic scenarios described below). Alternative approaches include (i) using alternative model structures in addition to changing parameters – these constitute the backbone of Cultural Theory (van Asselt and Rotmans, 1996) and exploratory modelling (Bankes, 1993), and (ii) minimax regret strategies (Loulou and Kanudia, 1999). Some other approaches are briefly described below.

5.2.1
Cross-impact analysis (CIA)

Qualitative insights are often generated about how different model parameters and policy alternatives interact. Cross-impact captures the consequence of an event *x* on the probability of occurrence of another event *y*. These cross-impact effects or causal probabilities are obtained by collating and systemizing expert judgments (Gordon and Hayward, 1968) on the development of multiple variables and their interactions in large-scale interdependent systems.[55] The Cross-Impact Balance Analysis (CIB) (We-

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[55] The complexity of a large-scale interdependent system does not lend such integration to purely qualitative, albeit reasoned analysis, while structural knowledge about underlying systems is too scant for quantitative system dynamics.

imer-Jehle, 2006) constitutes a specific and rather new approach, within the broad field of CIA, that provides a coherent and transparent approach to analytically integrate interdisciplinary sources of knowledge in scenario development. CIB allows a systematic consideration of combinations of input parameters, hence making the uncertainty and complexity of societal (and non-quantifiable) factors more explicit. This is by no means a *panacea* when it comes to addressing uncertainty in view of its reliance on the normative judgments of experts, which, unless elicited with care, are susceptible to heuristics and biases. Otherwise, the cross-impact approach provides a vehicle for upstream discussion of assumptions and desired outcomes (as in backcasting), either as preparatory steps to scenario analysis or in forging better system understanding by analysts (Weimer-Jehle, 2006). Moreover, the CIB approach can be used to generate a large of number of qualitative scenarios and identify system tendencies – or *basins of attractions* in the parlance of complexity theory – that can be useful to improve the robustness of energy policies as to alternative energy demand futures. One limitation of CIB is that it provides figures for a certain point in time only.

5.2.2
Stochastic scenarios

Advances in computing capacity have helped improve optimisation under uncertainty for large-scale problems. Many scenarios are deterministic as in worse-case, best-case or most-likely scenarios. These scenarios ignore the impact of different inputs – including interdependence among inputs – on modelling outcome. By definition, deterministic scenarios reduce insights and perceived uncertainties about the future. Stochastic or probabilistic scenarios can be obtained by using Monte Carlo simulations where uncertain inputs are represented by probability distributions. Different scenarios of *what could* happen and their *likelihood* are obtained as outcomes of Monte Carlo analysis. These stochastic energy scenarios, although rarely used or communicated, facilitate scenarios analysis and can be invaluable to policy-makers.

5.2.3
Real options theory

A real option is defined as the right, but not obligation, to undertake a business opportunity. It reflects the (managerial) flexibility to adapt decisions to unexpected developments (Dixit and Pyndyck, 1994). Real options can be used to analyse investment in the energy sector such as to evaluate the impact of an energy efficiency policy in relation to the possibility of a company or individual to postpone decisions until new policy uncertainty (e.g. implementation of new measures) and/or technological uncertainty is reduced. The diffusion rate of energy efficiency can thus be assessed through the lens of real options theory (Hassett and Metcalf, 1992; Chronopoulos et *al*., 2011), and associated policy and welfare impacts as well as energy demand levels evaluated.

5.2.4
Agent-based approaches

Agent-based modelling (ABM) provides another alternative to deal with the uncertainty and complexity that result from more realistic models of energy system transformations, e.g. by embedding technological development within societal contexts. ABM can serve dual purposes. Firstly, ABM enables the quantification of behaviour-driven models[56] and the development of objective models and scenarios. Examples include ABM analyses of consumer choices of new cars (Mueller and de Haan, 2009), or of policy interventions for technology diffusion (Sopha et *al*., 2011). Secondly, refinements to ABM can be made to bridge short-term operational goals and long-term transformation goals.[57] PRIMES (see Box 18 for a brief overview of the model) and TIMER (see section 5.1.1) are examples of agent-based models.

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[56] See, e.g. Helbing and Balietti (2011).

[57] See, for instance, Dijkema and Lukszo (2008).

Box 18: Overview of PRIMES model

A distinctive feature of PRIMES is the combination of microeconomic foundations of behaviour with engineering type models at a fairly high level of details while being compatible with long-term horizon modelling.

Typical Inputs	Analytical Approach	Selected Outputs
• GDP and sector-specific activity • Set of economic & environmental policies and constraints • Energy network infrastructure • Technical & economic characteristics of future technologies • Energy consumption habits and needs based on end-use services • Cost curves, energy efficiency potentials	• Behaviour of sector-specific agents simulated separately • Behaviour modelled in line with microeconomic theory, including habit & risk preferences • Prices determined by a set of energy markets that are cleared simultaneously • Investment is endogenously driven by expected profits and market imbalances	• Structure of energy demand by sector; energy use linked with activities • Transport activity, modes / means and vehicles • Set of market-clearing prices, including emissions if applicable • Impact indicators for diverse policies, e.g. for promoting technologies and efficiency

Source: Adapted from www.e3mlab.ntua.gr/e3mlab/PRIMES Manual/The PRIMES MODEL 2013-2014.pdf

6.

USEFULNESS AND LIMITATIONS OF MODELS AND SCENARIOS FOR ENERGY PLANNING

Kann and Weyant (2000) argue that policy insights from large-scale energy-economy models are relevant only to the extent that models agree on major recommendations. This is however rarely the case because modelling outcomes and scenarios depends on the final model structures, which are determined by (i) assumptions about the exogeneity and endogeneity of different system processes, (ii) a number of value judgments, e.g. about system parameters, and (iii) how model simplifications are introduced to render computations more tractable.

6.1 Diversity of scenarios and models

The diversity of scenarios produced by different organisations reflects divergent views on determinants of energy futures such as economic growth, the role of business and the extent of social adaptation. Backcasting can help steer upstream discussion on assumptions and the desired outcome of transitions. Often backcasting starts out with no modelling, but such heuristics can be better corrected for with analytical techniques that require scenario makers and energy-system modellers to examine their assumptions closely.

The choice of models also reflects different perceptions and sociocultural and environmental values, which determine how problems at hand are conceived and addressed. Techniques of analysis[58] are likewise imbued with similar assumptions and momentum that exists for particular policies. These assumptions should be clearly stated[59], whether for policy analysis or for engaging with different stakeholders. Energy modelling is often seen as a key aspect in large-scale, long-term planning. In view of the diversity of models, it is important to choose models that are fit for purpose. For instance, macro models (based on econometric modelling or general equilibrium analysis) may be more appropriate for national-level planning while micro-models are more suited for socioeconomic analysis. Factors that influence energy demand such as employment effects, rebound effects and the location of businesses are potentially better analysed with top-down as opposed to bottom-up models.

Therefore, when analysing future energy demand, it is essential to carefully match models with relevant qualitative scenarios and vice-versa. The risk of analysing scenarios (narratives and storylines) with incorrectly selected models is that of generating analyses and recommendations that are incongruous and raise controversy among the community of researchers and decision-makers alike. For instance, exploratory scenarios can be quantified by CGE models, bottom-up energy-system models or by

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[58] The techniques adopted by different organisations are often constrained by data and software availability and competencies.

[59] Many progress reports and public policy communications document the outcomes of analysis but the assumptions underlying the analysis are rarely stated. Taking different perspectives and using varying evaluation tools, analysts from different organisations do not reach the same conclusions. Lack of consensus creates significant controversy that can adversely affect public expectation.

agent-based models. The quantitative outcomes can be very different, even when the same qualitative scenario assumptions are fed into the model.

6.2 Importance of time horizons

Hedenus, Johansson and Lindgren (2013) make the following recommendations:

1. For short-term perspectives when energy infrastructures are largely intact, econometric based models and CGE models with short-term substitution elasticities between production factors may be more appropriate; some predictions are feasible.

2. Energy-system (bottom-up) models are recommended for planning horizons over decades as they allow for investigating the role of different technologies, while CGE – provided hybrid models are used and parameters are flexible – may help examine economic restructuring. Thus, for analysing longer-term horizons (50 years or more) as in the case of planning for current energy transitions, bottom-up models are potentially better as they allow for large-scale system restriction.[60]

3. For even longer horizons such as 100 years, when the system may undergo intermittent technological and socioeconomic shifts, quantitative models become less useful. The emphasis is better placed on building qualitative and an internally consistent picture of plausible energy system development. IAMs are very long-term quantitative energy-economy-environmental models that are used for that purpose and are primarily concerned with the climate-change impact of energy system transitions. IAMs, like many large-scale models, are highly modular in structure so they can accommodate a broad set of scenarios that rely on careful selection of the models. VLEEM (see section 3.1.3) developed by ENERDATA is one particular model that enables analysis of the evolution of demand with reasonable detail over a very long-time horizon.

6.3 Towards robust energy planning and strategies

Uncertainty and biases in energy scenarios and forecasts are likely to persist. Section 5 argued that it is vital to identify their multiple traits as they are embedded in data, model and foresight exercises. Over time, visions are likely to become increasingly contested and controversial. In this context, "[r]ather than generating foresights, the models should be seen as tools for generating insights and offering plausible pictures on how the future may develop in an internally consistent way" (Hedenus, Johansson and Lindgren, 2013), since, in the end, it only matters that energy policies be robust over a wide-range of output uncertainties based on variations in model inputs and alternative system dynamics (see Lempert et *al*. (2013a,b) for an overview of robust decision-making). There are energy models that are designed to help such robust decision-making approaches, e.g. MESSAGE-MACRO developed by IIASA.

6.4 Communicating scenario and modelling outcomes to policymakers

Model-based scenarios can provide very helpful and important decision support. To enhance the usefulness of their work, modellers should ensure that the underlying assumptions and model uncertainties are well communicated so that they can be integrated in the decision-making process.

The effect of induced technological change (Weyant and Olvason, 1999; Edenhorfer et *al*., 2006) and heterogeneous behavioural responses to policy also needs to be expanded. The delays created in reaping the full impact of policy need to be integrated in policy recommendations to maximise effectiveness, in particular where the timing of policy implementation is concerned.

Furthermore, the outcomes of scenarios and models, e.g. greenhouse gas emissions, policy variables such as tax

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[60] This said, the choice of models should be driven by the research and policy question, depending on which, top-down models may be more appropriate. The analysis for example of the impact of CO_2 taxes or any other policy measure that has an impact on multiple sectors of the economy is difficult with bottom-up models. Dynamic CGE (top-down) models are usually used for this kind of analysis for both medium (20-30 years) and long time horizons.

rates, and energy consumption levels, should be communicated to stakeholders and policy-makers in simple and easy-to-understand ways. For instance, misinterpretation of modelling results by decision-makers can be reduced if modellers make the effort to translate abstract results into everyday-life terms, such as “1 €/litre of diesel” instead of “400 €/tCO_2” carbon tax. Insights from behavioural economics, for instance, show that communicating about fuel efficiency using the measure of “miles per gallon” leads people to undervalue the benefits of replacing the most inefficient automobiles. Experimental evidence indicates that a change in communication (to “gallons per mile”) can promote smarter decisions about energy efficiency and energy use (Larrick and Soll, 2008).

Since information derived from energy models can change the preference of stakeholders and energy consumers (Trutnevyte et *al*., 2011), more than that of the computation itself, the true added-value of the modellers lies in their ability to select and communicate the most relevant information in the most useful format rather than producing hundreds of graphs and tables.

In recent years, a number of interactive online energy-calculator tools have appeared to inform policy-makers and the public at large about trade-offs within the energy system. Examples include the UK 2050 Calculator[61] and the Dutch Energy Transition Model[62], which has the additional feature of being able to select various scenarios. In changing societal perception of energy transitions, these tools can influence preference.

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[61] 2050-calculator-tool.decc.gov.uk

[62] pro.et-model.com

7.

CONCLUSION AND WAY FORWARD

This Concept Note reviews various scenarios and models that can be used to anticipate energy demand. It emphasizes some of the limitations, in particular those related to uncertainty in assessing demand in the future. The world will be shaped by energy efficiency improvements in all regions together with changes of policies. In Western Europe, energy efficiency and energy sufficiency are paramount to achieving the goals of the current wave of energy transitions. They will require a change in the paradigms of energy consumption and even lifestyle, including the rise of prosumerism (where energy consumers take on the additional role of energy producer). In this context, assessing the evolution of energy demand will require a multidisciplinary approach to understand the multifaceted drivers of the transition toward low-energy consuming economies. The broader regional and international context and policies will also have to be integrated in national plans for energy transitions. Such an inclusive approach poses challenges to both scenario developers and modellers because of a number of crosscutting issues that are often hard to quantify, in part because of the absence of historical precedence.

Bearing in mind the trade-offs that exist between simple and complex models, it would be useful to explore: (i) the relevance of including behavioural drivers of energy demand for different uses of models and scenarios; (ii) how quantitative information about the diverse drivers can be obtained in objective and verifiable ways; (iii) the extent to which behavioural economic frameworks should replace existing neo-classical paradigms; (iv) the relationship between short-run and long-run behavioural change – while policy can effectively effect short-run behavioural changes, whether and how these can be sustained over long horizons is an issue that is important to address; (vi) instances in which insights from behavioural economics can help improve the effectiveness of traditional interventions in energy policy and when they could crowd out those more effective traditional instruments; and (vii) how the coherence between scenarios, including explorative qualitative context-scenarios, and energy models can be improved to better assess future energy demand and inform strategic and policy decisions on the governance of energy transitions.

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