2°C through different lenses

Evaluating long-term energy system change for a 2°C-constrained world

M. A. E. van Sluisveld

2°C through different lenses
Evaluating long-term energy system change for a 2°C-constrained world
M.A.E. van Sluisveld, 2017

The research reported in this dissertation has been carried out at the 'Copernicus Institute for Sustainable Development', Utrecht University, and the 'Climate, Air and Energy' department of the PBL Netherlands Environmental Assessment Agency. The research leading to the results has received funding from the European Union's Seventh Framework Programme FP7/2007-2013 under grant agreement n° 282846 (LIMITS) and n° 603942 (PATHWAYS).

ISBN: 978-94-6299-615-1
Cover illustration: A.E.F.M.W. van Sluisveld, M.A.E. van Sluisveld
Layout & Print: Ridderprint (Ridderprint.nl)

2°C through different lenses

Evaluating long-term energy system change for a 2°C-constrained world

2°C door verschillende lenzen

Het evalueren van lange termijn energiesysteemverandering in het licht van de 2°C klimaatdoelstelling

(met een samenvatting in het Nederlands)

Proefschrift

ter verkrijging van de graad van doctor aan de Universiteit Utrecht op gezag van de rector magnificus, prof. dr. G.J. van der Zwaan, ingevolge het besluit van het college voor promoties in het openbaar te verdedigen op dinsdag 4 juli 2017 des middags te 4.15 uur

door

Maria Anna Elisabeth van Sluisveld

geboren op 14 mei 1988 te Zoetermeer

Promotor: Prof. dr. D.P. van Vuuren
Copromotor: Dr. A. F. Hof

Table of Contents

Units and abbreviations

°C	degree Celsius
/cap	Per capita
/min	Per minute
/yr	Per annum
AIM-Enduse	The Asia-Pacific Integrated Model with a focus on end-use technologies (maintained by the National Institute for Environmental Studies of Japan)
ANCRE	French National Alliance for Energy Research Coordination
ASHP	Air Source Heat Pump
AR4	The fourth Assessment Report of the Intergovernmental Panel on Climate Change
AR5	The fifth Assessment Report of the Intergovernmental Panel on Climate Change
BAT	Best Available Technology
BECCS	Bioenergy and Carbon Capture and Storage
BEV	Battery Electric Vehicle
BMUB	Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety of Germany
CCC	Committee on Climate Change
CCS	Carbon Capture and Storage
CGE	Computable General Equilibrium
CH_4	Methane
CO_2	Carbon dioxide
CSP	Concentrated Solar Power
DE	Germany
DEA	Danish Energy Agency
DECC	Department of Energy and Climate Change in the United Kingdom
EED	European Energy Efficiency Directive
EJ	Exajoule (1 EJ = 10^{18} Joule)
EMF	Energy Modelling Forum
ETS	European Emission Trading System
EU	European Union
FAIR	Framework to Assess International Regimes for the differentiation of commitments (maintained by the PBL Netherlands Environmental Assessment Agency)
FC	Fuel Cell

GCAM	Global Change Assessment Model (maintained by the Joint Global Change Research Institute at the Pacific Northwest National Laboratory)
GDP	Gross Domestic Product
GJ	Gigajoules (1 GJ = 10^9 Joules)
GHG	Greenhouse Gas
Gt	Gigatonne (1Gt = 10^9 tonne)
GW	Gigawatts (1 GW = 10^9 Watt)
H_2	Hydrogen
HDD	Heating Degree Days
HLF	Heavy Liquid Fuel
IAM	Integrated Assessment Model (plural: IAMs)
IAMC	Integrated Assessment Modelling Consortium
IAV	Impacts, Adaptation and Vulnerability
ICE	Internal Combustion Engine
IMAGE	Integrated Model to Assess the Global Environment (maintained by PBL Netherlands Environmental Assessment Agency)
IPCC	Intergovernmental Panel on Climate Change
KNET	Knowledge Network for Energy Transitions
kWh	kilowatt hour
L	litre
LBNL	Lawrence Berkeley National Laboratory
LCOE	Levelised Costs of Electricity
LDV	Light Duty Vehicle
LIMITS	European research project on Low climate Impact scenarios and the Implications of required Tight emission control Strategies
LLF	Light Liquid Fuel
LTECV	The French Energy Transition for Green Growth Act (Loi de Transition Énergétique pour la Croissance Verte)
LULUCF	Land-Use, Land-Use Change and Forestry
m^2	Square meter
MARKAL	Market Allocation model maintained by the Energy Technology Systems Analysis Program (ETSAP) community
MESSAGE	Model for Energy Supply Strategy Alternatives and their General Environmental Impact (maintained by the International Institute for Applied Systems Analysis)
NGO	Non-Governmental Organisation (plural: NGOs)
MIP	Multi-model Inter-comparison Project (plural: MIPs)

MLP	Multi-Level Perspective
MNL	Multinomial Logit
NEEAP	National Energy Efficiency Action Plan
NREAPs	National Renewable Energy Action Plans
Mt	Megatonne (1 Mt = 10^6 tonne)
NL	The Netherlands
N_2O	Nitrous oxide
NEDE	Non-Energy Demand and Emissions model
OECD	Organisation for Economic Co-operation and Development
PATHWAYS	European research project on transition pathways to sustainable low-carbon societies
PCW	Plastic Consumer Waste
PHEV	Plug-in Hybrid Electric Vehicle
ppm	Parts per million, reflecting the number of greenhouse gas molecules in the total number of molecules of dry air
PV	Photovoltaic
RD&D	Research Development and Demonstration
RED	European Renewable Energy Directive
REMIND	Regional Model of Investments and Development (maintained by the Potsdam Institut für Klimafolgenforschung)
REMG	Residential Energy Model Global of the TIMER model
REN21	Renewable Energy Policy Network for the 21st Century
SiMCaP	Simple Model for Climate Policy Assessment (maintained by PBL Netherlands Environmental Assessment Agency)
SSP	Shared Socioeconomic Pathways
SRES	Special Report on Emission Scenarios
SRRES	Special Report on Renewable Energy and Climate Change by the IPCC
STRN	Sustainable Transitions Research Network
SWE	Sweden
GEA	Global Energy Assessment
T$	Trillion USD$ (1 T$ = 10^{12} USD$)
TIAM-ECN	The Integrated Assessment Model (maintained by the Energy research Centre of the Netherlands)
TIMER	The IMAGE Energy Regional model (maintained by the PBL Netherlands Environmental Assessment Agency)
TMB	Travel Money Budget
TRAVEL	The global transport model for the TIMER model
TTB	Travel Time Budget

USA	United States of America
USD$	United States Dollars
UK	United Kingdom
UKTM	United Kingdoms' TIMES Model
w/	with
W/m^2	Radiative forcing in watts per square meter
w/o	without

Chapter 1

Introduction

1 Introduction

1.1 Global warming and policy decisions

Global warming has been identified as a possible consequence of increasing levels of greenhouse gas (GHG) emissions in the atmosphere since the late 19th century (Arrhenius, 1896). Since then, interest in this topic has grown and by now the human contribution to these greenhouse gas emission levels, our understanding of the biophysical system and the possible impacts on human livelihoods are studied in detail by many research disciplines (Moss et al., 2010). Notable endeavours advancing the understanding of global warming and the impacts of human-induced climate change are found in the work done by the *Intergovernmental Panel on Climate Change* (IPCC), a scientific and intergovernmental body under the auspices of the United Nations. The IPCC is the international organisation that coordinates the evaluation of science related to climate change, and has provided the scientific underpinning for governments at all levels to develop climate related policies since the early 1990s (IPCC, 2017).

The ever-increasing scientific evidence on global warming has resulted into developing collective political ambitions to limit GHG emissions and global mean temperature increase. Examples of this are the *Kyoto Protocol* in 1997, stipulating legally binding emission reduction objectives for governments for the next decade (UN, 1998); the *Cancun Agreements* (UN, 2010) in 2010 in which the global community agreed upon limiting global mean temperature increase by no more than 2°C relative to the pre-industrial level[1] and the *Paris Agreement* (UN, 2015) in 2015, which strengthened the former communicated ambitions to *well below* 2°C (and possibly even 1.5°C).

A global commitment to mitigate GHG emissions and to limit global warming is considered a first vital step to preventing damage to the human system. However, given (1) the relatively long temporal scales in which global warming materialises (as seen from the human perspective), (2) the inevitable inertia faced in both natural and human systems (such as considered in the long atmospheric lifetime of some greenhouse gasses or vested interests in existing human systems), and (3) the numerous complex

1 Pre-industrial refers to the period before 1750, though temperature change is measured over the longest global surface temperature dataset available, using the average over the 1850-1900 as the reference point (IPCC, 2014d). Temperature change is associated with the increase in the global atmospheric concentrations of carbon dioxide, methane and nitrous oxide gasses, which levelled around 280 ppm during pre-industrial times (IPCC, 2007). Concentration levels of 450 ppm or lower are considered *likely* to maintain global warming below 2°C over the 21st century compared to the pre-industrial level. For comparison, the concentration level in 2011 was estimated at 430 ppm (with an uncertainty range of 340 to 520 ppm) (IPCC, 2014c)

and ever evolving natural-human system interactions of many kinds, operating on multiple scales, it raises the question *how* a long-term objective as negotiated by the global community can be achieved and what this means to todays' practices.

1.2 Informing about low-carbon transitions

Over the past decades, many researchers have embarked on a quest to develop tools and methods to provide an answer to *how* global warming can be limited to a certain degree, with specific focus on human society and its activities. Several important streams of research, methods and tools can be distinguished in literature that are concerned with developing insights on (1) how human societies can move away from emitting GHG emissions via so-called *low-carbon transitions* and (2) testing whether these are in line with the agreed upon 2°C objective. Overall these research directions, methods and tools allow themselves to be grouped under three analytical research lenses:

1) *The historical reference lens:* Lenses looking more into processes of the past to draw lessons for the future (devising documented history as a source of reference);
2) *The expert knowledge lens*: Lenses focusing more on the interpretations of experts on current transition processes to extrapolate this directly into the future (devising knowledge of todays' change makers to gauge the orientation of the future);
3) *The model-based scenario lens*: Lenses attempting to focus directly on future change by integrating and extending available knowledge to explore the consequences of today's decisions. Alternatively, they are used to elaborate on needed change to meet a certain target (structuring knowledge on complex system dynamics and consistently testing scenarios of future change via the use of computational models).

The next sections will further discuss how each of these analytical lenses inform about future low-carbon transitions.

1.2.1 The historical reference lens

Over time society has lived through and moved away from several inventions and widely applied processes and practices. As such history provides a wealth of information on (long-term) societal and technological change, from which we can draw information about underlying behaviour of (global) systems change. Two specific strands of literature can be recognised which both seek to either (1) structure fragmented historical data to find universal patterns of systems behaviour and (2) theorise on how this information can be used to drive future change:

- *Technological transitions*: One strand of literature focuses on technological change and innovation systems. Studies in this category focus on the catalysts (input) and results (output) of innovation processes, as to identify and isolate the effect of, for example, policy on systems change and technological development stages (Wilson, 2012). Alternatively, other scholars focus more on the final outcomes and impacts of technological change (materialisation of change) to aggregated energy systems. Many of the studied driving elements are rather intangible and specific to a certain technology or process of interest; hence these only allow to be approximated via the use of quantitative proxy indicators. For example, public expenditures or investments on research or demonstration projects are used to underpin phenomena of knowledge accumulation, strengthening of actors and institutions and improving performance of technologies. The results of innovation policies, such as the adoption and use of technologies, are observed via cumulative production data and associated price reductions (as a result of the economies of scale) (Wilson, 2012). Scholars looking more into the final outcomes and impacts of technological change generally study the duration and extent of past transitions as to deduct technological diffusion patterns and their effects to the overall system (Grubler, 2012; Höök et al., 2012; Smil, 2000).

- *Socio-technical transitions:* A second strand of literature recognises that humans are significant agents of change and focuses more on studying the *type* of actors involved, *when* something happened and *how* this influenced complex socio-technical systems and the rule-sets in society (Sovacool, 2016). By analysing and codifying the activities of agents along the diffusion of technologies, it may result in a different picture than when simply looking at the outcomes of a transition. These studies thus provide insight in the actors who have propelled change and their ramifications to the existing socio-technical system, which are expected to provide valuable insights on how to recognise and mobilise future system change (Rohracher, 2008). Several socio-technical transition conceptualisations exist to date, which either focus on identifying and explaining specific transition pathways (Geels and Schot, 2007) or theorise on active intervention processes at the level of governments, sectors or cities (Markard et al., 2012).

1.2.2 The expert knowledge lens

Next to drawing insights from past events, one can also gain insights in transition developments by engaging with those confronted with and invested in current transitions. This analytical lens can be classified as the field of research that concerns itself with acquiring information that has not yet been codified in literature (state-of-the-art) or to examine the values and beliefs of stakeholders or communities. In this regard, two strands of literature can be recognised:

- *Expert elicitation:* One strand of literature under the expert lens is oriented towards gathering confidence intervals around decisions that are of interest to the decision makers. Expert elicitations are widely used for uncertainty assessment when no or little direct empirical evidence is available to inform a decision maker (Refsgaard et al., 2006). Expert elicitations deliver subjective probability distributions which reflect the beliefs of professional experts. Via structured elicitation protocols outcomes are made as credible as possible and traceable to its assumptions. Expert elicitations have been devised in a similar fashion as system innovation assessment under the historical lens, by drawing insights on system transformation input metrics (such as [public] research and development expenditures) to consider the effects on the evolution of future (energy) technology costs and performance (output which has not yet come to be) (Bosetti et al., 2016). Expert elicitations have also been used in more broader assessments to unravel potential courses of development, by deducting probabilities in decisional trees and the interdependencies of various sequences as found in cross-impact analysis (Weimer-Jehle, 2006). Alternatively, expert elicitations have been used to gather information about likelihoods and barriers to (technological) implementation (Vaughan and Gough, 2016).

- *Extended peer community:* Limiting global warming to no more than 2°C is a complex subject enshrined by value conflicts and risk perceptions related to climate and systems change. It brings about several social, economic, environmental and ethical concerns related to scientific and technological development, which demands other forms of knowledge creation and the inclusion of other views. Stakeholders are therefore considered to add to the quality of knowledge in long-term planning and can simultaneously be considered an important method for quality control of long-term perspectives (Van der Sluijs, 2002). Unlike earlier described methods, extended peer review would thus place more emphasis on the *shaping* rather than the *predicting* of the future (Rohracher, 2008). Extended peer community can be used in drawing insights in how system change is perceived in so-called "mental models" or, if combined with integrated assessment modelling (next section), provide a more explicit social dimension to future change studies (Voinov et al., 2014).

1.2.3 The model-based scenario lens

Various models can be used to explore the outcome of change over time, including (1) economic models, (2) energy system models and (3) integrated assessment models. Although all models provide a perspective on system change, the most comprehensive model accounting for interactions and feedbacks between the environmental and human system is the integrated assessment model (IAM). Integrated assessment models couple the knowledge of the physical sciences (such as physics, chemistry and biology) and social sciences (such as economics, psychology, sociology, and anthropology) into a single framework (Weyant, 2009). This knowledge is usually captured in a multitude of mathematical formulations, which combined form a quantitative computational model. Such computational models allow us to learn about the complexity of global change and the implications of change on society over a specified window of time. Integrated assessment models are mostly used to (1) explore different futures, or to look into the (2) required change needed to meet a predetermined policy objective. Two strands of literature can be mentioned that show particular relevance to informing about long-term future change, which cofounds with the *type* and *resolution* of the model being used (based on Edmonds et al. (2012)):

- *Highly aggregated IAM studies (cost-benefit):* Highly aggregated IAMs are considered to be relatively simple and stylised models that weigh the costs of negating the impacts of climate change to the economic benefits of reduced impacts. Studies utilising highly aggregated IAMs are concerned with topics such as social cost of carbon or optimal trade-offs over time of (in)action and impact. The literature reporting on the outcomes of highly aggregated IAMs are usually associated with a specific model, such as FUND (Tol, 1997) or DICE (Nordhaus, 1992).

- *High resolution IAM studies (policy optimisation):* High resolution models originate from a similar concept as the highly aggregated IAM studies. However, where highly aggregated IAMs fail to provide more details on natural and human system change, the high resolution IAM is specifically designed to emulate detailed representations of human activities and their impacts to the global system, such as total GHG emissions accumulating from more specified human activities (demand for services, use of energy) and the climatic response (see also Box 1). In that respect, high resolution IAMs have been considered a key instrument in informing the policy maker concerned with global warming on the implications of specific policies and low-carbon energy strategies.

Box 1: What is Integrated Assessment Modelling?

Integrated assessment models (IAMs) are quantitative computational models that connect selected disciplinary conceptualisations of global change together in mathematical formulations (denoted as "inside disciplines" in Figure 1-1). IAMs have emerged since the 1970s, either as an expansion of existing global energy-economy modelling endeavours or anew from scratch development (Kowarsch, 2016; Rotmans and van Asselt, 2001; Weyant, 2009). Over time, various IAMs have been developed and the IAM discipline is still in development, due to (1) computational technology advancements, (2) scientific advancements (e.g. via interaction with "outside disciplines", see Figure 1-1) and (3) increasing political interest to limit global warming.

The IAM genre addressed in this thesis can be classified as the high resolution IAM (Edmonds et al., 2012), which cover various human system developments and natural system elements. High resolution IAMs are used to provide insights on the course of system change over time, to reflect on considered feedbacks and to evaluate uncertainties. IAMs typically disaggregate the world into multiple (macro)regions and calculate with yearly or decadal time steps (Moss et al., 2010). IAMs are used to develop emissions scenarios and to quantitatively estimate the implications of policy decisions on energy supply, energy demand (amongst others, industry, mobility and the residential sector) and land-related activities (see Figure 1-1 for an illustrative example).

Two different types of high resolution IAM models can be distinguished, roughly classified as *top-down* and *bottom-up* models. Top-down models typically include a detailed macro-economic representation, although this is usually limited to one to three aggregated economic sectors due to computational limitations. Bottom-up models, on the other hand, are able to represent processes and markets in one or more sectors in detail, while treating the rest of the economy exogenously (Kriegler et al., 2015). Scenarios aligned to the 2°C objective at the end of the century may achieve this goal via perfect foresight of future markets and future developments or with more myopic or no foresight. In the latter case, (market) equilibriums will be considered recursively for each specified point in time. Both methods adhere to a lowest-cost paradigm, seeking a first-best solution on the merits of the lowest total costs over time.

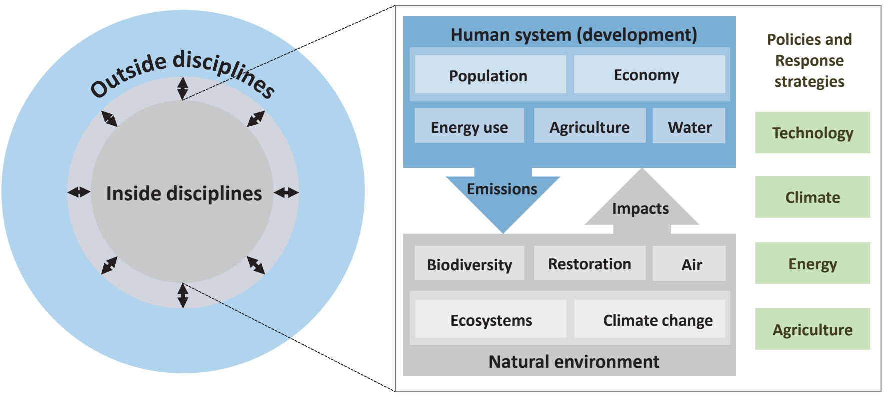


Figure 1-1 - Very simplified conceptual overview of integrated assessment modelling as assumed in this thesis. The inside disciplines are accountable for the performed assessments, although there is continuous dialogue with disciplines outside of the field of current demarcated integrated assessment

1.2.4 Comparing the analytical lenses

Each analytical lens utilises its own methodologies to look at future change, with differences in the (1) analytical and (2) temporal resolutions taken into considerations, and differences in scientific orientation in terms of their (3) viewing direction (reflexive or prospective), (4) types of metrics considered (qualitative or quantitative) and (5) treating uncertainties and diversities (pluralism or determinism). Although the considered streams of literature within each analytical lens may combine a variety of different methodologies, creating overlaps between the analytical lenses, they expose rather distinct limitations and opportunities. In the following section a brief (non-exhaustive) overview of strengths and weaknesses is provided for each analytical lens:

- **The historical reference lens:** Historical evidence may provide insights on the *speed* and *scale* of resource mobilisation that generated the necessary knowledge and actor base for sustained development and diffusion of new services and technologies (Wilson and Grubler, 2013). However, the research fields under this analytical lens can be characterised as wide and diverse, devising metrics of both quantitative and qualitative nature, offering insights on varying temporal scales and utilising both pluralism and determinism into their assessment. The historical reference lens is therefore characterised as providing fragmented images of systems change on a high specific case-study level. Several community initiatives have been undertaken to unify and strengthen the understanding in various transition conceptualisations, such as the *Sustainable Transitions Research Network* (STRN) (www.transitionnetwork.org) and the discontinued *Knowledge Network for Energy Transitions* (KNET) (Grubler, 2012), though specific challenges remain. Specific challenges are the considered subjectivity in notions of the course of development in (energy) system transitions or the included analytical biases in the used (proxy) indicators (e.g. representing only a single innovation phase). Moreover, given the reflexive viewpoint of many analyses, historical transitions may not provide the best reference for possible future change. Historical events may have been, for example, accidental or circumstantial and do not represent system changes that are more planned, coordinated or developed under specific governmental pressures (Sovacool, 2016).

- **The expert knowledge lens:** Experts have the ability to interpret the wealth of (tacit) information about current societal movements and consider the implications for the future. Collecting this knowledge, by means of expert elicitations, has the advantage of testing hypotheses and gauging the uncertainties that move beyond the status-quo, which cannot be distilled from historical references (Bosetti et al., 2016). Moreover, a broader inclusion of expertise yields notions of desirable and probable directions of future change as well as collects varying or contrasting perceptions on future change. However, experts may be liable to many cognitive biases and heuristics, which may lead to inaccuracies in articulated beliefs or expectancies on future change. Another limitation is considered for data comparability, given how research is commonly carried out by various research groups, in different periods of time and with different formats (Bosetti et al., 2016). Including (broader) expertise may also be regarded as narrowed down to a specific object of interest (Weimer-Jehle, 2006), which limits its contribution to a broader discussion on more aggregated systems change and low-carbon transitions in line with limiting global warming to no more than 2°C.

- **The model-based scenario lens:** Integrated assessment models encapsulate our current understanding of the numerous interactions and feedbacks of natural and human systems. They are instruments that allow quick prototyping of scientific or policy-relevant concepts of change in a structured and quantitative framework (Rotmans and van Asselt, 2001). In that respect, IAMs support us in providing insights on the influence and total impact of human activity on specified control variables. Moreover, when used in participatory approaches, they may engage stakeholders to think about future transitions and therefore allow for social learning (Voinov et al., 2014). However, given its attempt to provide a holistic and quantitative perspective, IAMs unintendedly impose various systemic biases by (1) focussing on elements that can solely be captured in (simplified) mathematical models and quantified parameters and (2) include (un)conscious value commitments, beliefs and fuzzy assumptions within the model syntax and parameterisation (such as found in the distribution of choice, human behaviour and the valuation over time and across generations) (Edmonds et al., 2012; Risbey et al., 1996; Schwanitz, 2013; van Asselt and Rotmans, 2002). As a result, modelling outcomes may be disputed on the basis of being an artefact of the model and modeller rather than being a learning tool for studying scenarios of future change and system responses. Recognised shortcomings are usually negated by including these into scenario narratives which may then implicitly account for elements that cannot be captured in mathematical (and therefore deterministic) formulations (e.g. the social dimension [actors] as well as the diversity in future perspectives [options]). Perhaps as a result of these epistemic difficulties, the IAM community has become a well-connected research community over time, allowing for shared methodological development, coordinated research and enhanced conceptual learning in multiple networks (such as the *Integrated Assessment Modelling Consortium* (IAMC) or the *Energy Modelling Forum* (EMF)).

Each analytical lens thus offers only a partial view of future system change, with a different understanding of low-carbon transitions and a different focus on the dynamics that invoke change. As a result, each analytical lens provides a different narrative of where a low-carbon transition is headed or should be heading. In the light of the 2°C objective, the analytical lens that can bring long-term systems change in relation to specific temperature increase is of prime interest. As such, the integrated assessment of global change, captured within IAMs, will be a central theme throughout this thesis. In the following section a more in-depth description is provided of the interpretation of long-term change through the lens of IAMs.

1.3 2°C in the light of the IAM-lens

Integrated assessment of global change combines perspectives of the physical and social sciences in one structured and consistent framework, as to study the interaction and feedback mechanisms between human and natural systems. As these conceptualisations of global systems change are captured in mathematical formulations and compiled into computational models, they are able to extend todays' knowledge over a predetermined time horizon. For example, studies that extent todays' knowledge describe a global mean temperature increase in the order of 3.6-5.2°C (assuming "current policies" and with a 90% likelihood) at the end of the century (Rogelj et al., 2016a).

Alternatively, IAMs can also be used to project pathways in which additional system pressure is imposed, as a means to study the associated changes in the modelled global system. By specifically linking the IAMs to the 2°C climate objective, so-called 2°C pathways are created. 2°C pathways utilise the concept that the volume of total cumulative greenhouse gas (GHG) emissions in the atmosphere can be considered a linear predictor of global warming over time (Meinshausen et al., 2009; Rogelj et al., 2016b). This makes GHG emissions the key control variable to limiting global warming. With knowledge of todays' (growing) GHG emissions in the atmosphere and the knowledge of how much total GHG emission remains in line with the 2°C objective, it illustrates the remaining "carbon budget" that is available to society.

How society could limit emitting GHG emissions to the atmosphere has been intensively studied via the use of IAMs, whose most recent collective knowledge has been published in the 5th Assessment Report (AR5) by the Intergovernmental Panel on Climate Change (IPCC) (Clarke et al., 2014) (see Figure 1-2). The 2°C pathways to date describe the influence of policy choices to the considered collective mitigation effort. IAMs can, for instance, point at (1) the impact of excluding specific technologies in the mitigation strategy or (2) the impact of delays in global coordinated action and (3) the associated costs for embarking on such a long-term strategy.

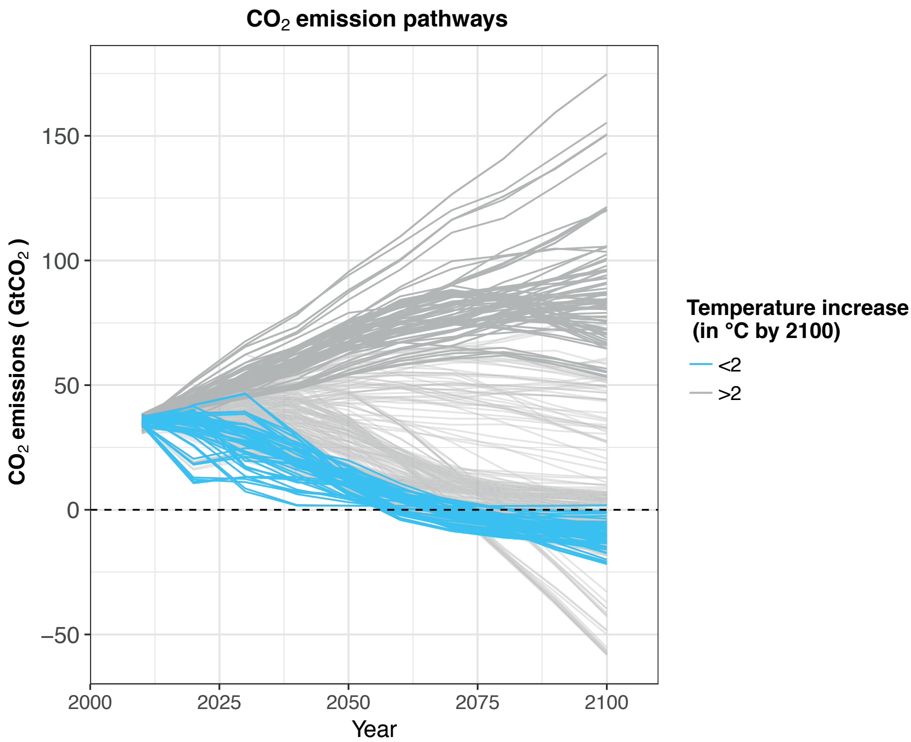


Figure 1-2 - overview of all the pathways as considered in AR5. Only the blue band is considered to meet the macro-political goal of limiting global warming to no more than 2°C. Data from IPCC (2014a).

While these 2°C pathways have been helpful in informing negotiators and heads of state during the Paris Climate Agreement (G7, 2015), they have also been criticised. For instance, the 2°C pathways have been criticised on their (i) assumptions on large-scale availability of (prospective) technologies, such as considered for "negative emissions" technologies (allowing the 2°C pathways to go below zero, as illustrated in Figure 1-2) (Anderson and Peters, 2016; Fuss et al., 2014), (ii) assumptions on the scaling behaviour of technological and non-technological properties within the IAM (Iyer et al., 2015), (iii) assumptions about (techno-economic) system transitions (Höök et al., 2012; Smil, 2008), (iv) ignoring the much more substantial changes needed on the local levels (Grübler, 2004) and (v) not appropriately reproducing social behaviour responses (Li, 2017; Victor, 2015)(see also box 2 for further information on the influences).

Moreover, although IAMs are assumed to be helpful in informing about key elements of long-term systemic change, such as, amongst others: (a) rates of deployment of energy technologies, (b) rates of reductions in global and regional emissions, and (c) links to other policy objectives such as energy security (Clarke et al., 2014), insights are

Box 2: What can IAMs tell us about 2°C pathways?

How we think about the available leeway: The "carbon budget" principle introduces the policy concepts of *stabilisation* and *overshoot* (see Figure 1-3). Stabilisation is the mode in which a carbon budget is maintained, whereas overshoot represents the mode in which the carbon budget can be exceeded given the availability of additional measures to mitigate the effects. Overall, the largest part of 2°C pathways in AR5 adhere to the overshoot-type of policy mode. The 2°C narratives in AR5 thus include explicit representation of processes and technologies that remove the surplus of carbon dioxide (CO_2) emissions from the atmosphere. Removal of carbon from the atmosphere may occur via natural processes, such as the uptake by oceans or the terrestrial biosphere. However, more rapid and coordinated removal processes are considered as well, which can be grouped into biological or non-biological (industrial) capture and biological or geological storage of carbon dioxide (Tavoni and Socolow, 2013). A prevalent type of carbon removal in 2°C pathways by AR5 is afforestation which combines biological capture with biological storage, but to a far greater extent the combination of biomass conversion to energy (bio-energy) with carbon capture and storage (CCS) (referred to as BECCS) is utilised. The large-scale use of BECCS represents the phenomenon of "net negative emissions", in which more carbon emissions are removed from, than emitted to, the atmosphere (portrayed by CO_2 emission pathways going below zero).

How we think about social inertia: Another important aspect of 2°C pathways involves the *timing* of (coordinated) global action. Timing in this case reflects the ability of governments to (collectively) curb emissions over time, in which failure implies a growing level of GHG emissions in the atmosphere over time. In order to balance the higher GHG emission levels within a fixed carbon budget associated with the 2°C objective, this subsequently requires greater mitigation efforts over a shorter period of time (see Figure 1-3). Mitigation strategies that are currently assumed to be *optional* may then become *a must* if the 2°C objective is to be obtained. Policy delays may thus affect the flexibility of a system to adapt and simultaneously increase the total costs to meeting the 2°C climate objective.

How we think the human system will evolve: Although IAMs generally model natural and human systems via a rather universal approach, based on (energy) engineering principles connecting consecutive chains of energy service demands to the use of primary energy carriers (Van Vuuren, 2007), differences in model-based low-carbon transition pathways may still exist. These differences arise from differences in (1) model structure, (2) solution method, (3) system representation and (4) data input (Chaturvedi et al., 2012; Kriegler et al., 2015; Macknick, 2011). Differences in interpretations, assumptions and implementation may lead to different sequential patterns of system change as well as differences in depicted scales.

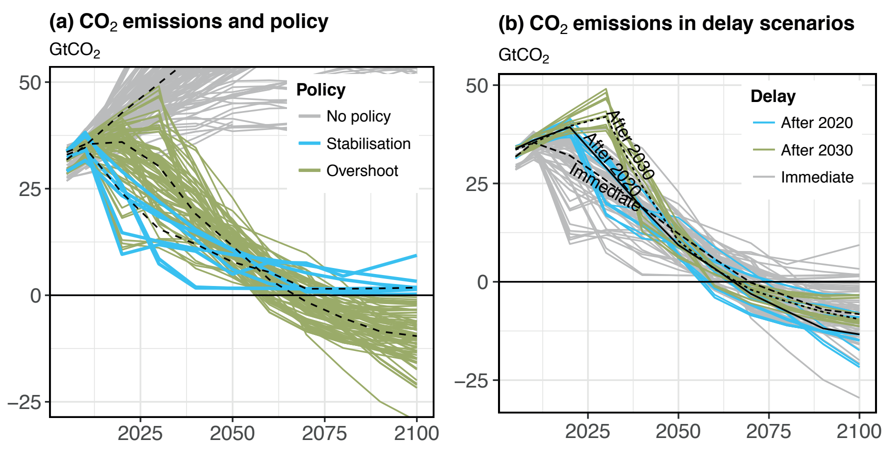


Figure 1-3 - Illustrative overview of global CO_2 emission pathways (in $GtCO_2$) and the multi-dimensionality within the range of 2°C-proof trajectories. Data from IPCC (2014a).

generally provided on the basis of simplified and idealised assumptions (such as the functioning of markets, and non-economic and non-technological elements). This is necessary to make model analysis more heuristic in providing policy-relevant decision support. However, it also means that the models often ignore the diversity and sub-optimality of real world system processes, which may impose a substantial (positive and negative) contribution to attaining the 2°C target (Clarke et al., 2009; Iyer et al., 2015; Riahi et al., 2015).

1.4 "2°C through different lenses"

Limiting global warming to no more than 2°C raises questions about *how* such a long-term objective can be achieved. As outlined throughout section 1.2, various analytical lenses are available that provide insights on future system change and low-carbon energy transitions, each with a different focus and orientation towards answering the *how* question. These partial views pose challenges in providing (1) a univocal (long-term) perspective, (2) a set of undisputed holistic metrics that can be measured and monitored over considerable periods of time and (3) a method to represent the diversity in human society and system change.

Integrated assessment models (IAMs) can be considered the lead tool to inform about long-term transformative change aligned to a long-term climate objective. As such, IAMs may provide the first indication of the needed efforts to meeting the 2°C objective. However, given the open and fundamentally unknown character of future systems change there are many approximations and uncertainties embedded into the IAM structure which both influence and limit the IAM interpretation of future system change (van Asselt and Rotmans, 2002).

As IAMs are simplified representations of the global system, it raises the question whether IAMs may sufficiently represent the opportunities and challenges associated for a 2°C constrained world. Secondly, as IAM results have been used in the past to underpin climate policies or international negotiations, it is also of interest to consider how comprehensive integrated assessment models are perceived and devised in policy planning processes.

As such, the main goal of this thesis is to provide a more holistic perspective on whether simplified representations of complex system change by IAMs can hold in the view of other analytical lenses. This results in the overall research question:

- *What additional insights on the opportunities and challenges of meeting the 2°C climate objective can be obtained from a more detailed analysis and development of model-based scenarios in the context of alternative perspectives?*

The main research question is subdivided into the following sub-questions:
- ***Research question 1:*** *What insights do regional outcomes of model-based scenarios provide?*
- ***Research question 2:*** *What insights are provided by evaluating 2°C model scenario results to other analytical lenses?*
- ***Research question 3:*** *What insights can be obtained by developing 2°C scenarios based on the information alternative perspectives provide?*
- ***Research question 4:*** *How are integrated assessment models used in policy planning processes towards a low-carbon society?*

In order to gain the insights required to answer the research questions posed above, as well as to get a more holistic perspective on the opportunities and challenges of limiting global warming to no more than 2°C, this thesis deploys a mixed-methods approach utilising different analytical lenses, analytical levels, research activities and modelling exercises.

The high resolution IAM will be used as the instrument providing model-based scenarios in line with 2°C. Depending on the research question, insights will be drawn from one specific integrated assessment modelling framework or a combination of multiple comparable frameworks (in so-called multi-model inter-comparison projects).

The main focus will be on the tendencies of the human system to adapt to a low-carbon society aligned to a 2°C objective. Depending on the research question, the focus will be on one or more economic sectors considered with energy supply or energy demand.

In evaluating these pathways towards 2°C, one can consider a (1) *within*, (2) *between* and (3) *beyond* disciplinary view, in which one respectively puts the IAMs and IAM performance at its core, in which IAM output is confronted to other knowledge bases for a direct comparison and where one moves beyond the disciplinary boundaries of IAMs to place IAM outcomes in a broader analytical context and spectrum of value. In the next section further elaboration is provided on the applied evaluation framework.

1.5 Evaluation framework

Several frameworks and good practices have been published over time that ask the question how IAM outcomes can be tested on their representativeness (see e.g. Jakeman et al. (2006); Risbey et al. (1996); Schwanitz (2013); Wilson et al. (2017)). In general two avenues for analysis can be identified, which are (1) the comparison of future modelled outlooks to observational data on corresponding variables and trends and (2) testing our conceptual understanding via comparison of future systems change over extended periods of time with competing or other (outside) disciplinary fields (Risbey et al., 1996; Schwanitz, 2013; van Vuuren et al., 2010) (see Figure 1-4 for an illustration).

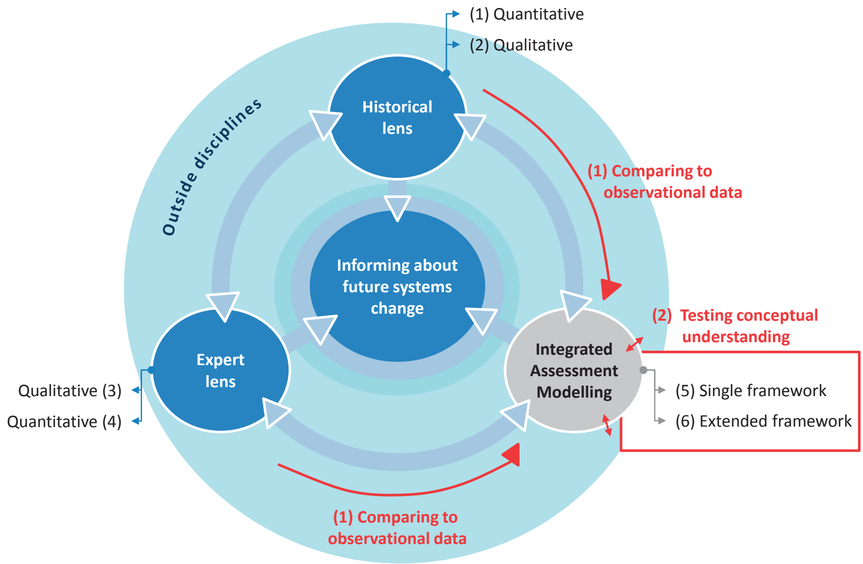


Figure 1-4 - Conceptual overview of the various available lenses to inform about future systems change, with specific evaluation study directions per lens.

The following sections will briefly describe several different perspectives and approaches available to evaluate IAMs and their depictions of future system change. The focal point will particularly be on methods that have a direct connection to IAMs. Although it is acknowledged that other methods exist to derive perspectives on long-term systems change, e.g. via formulating mental models (Voinov and Bousquet, 2010) or detailed narratives of future change (Elzen et al., 2004), these will go beyond the scope of this thesis.

1.5.1 Using the historical reference lens

As described earlier, several strands of literature provide insights on universal patterns and system behaviours. These "rules-of-thumb" can be utilised in IAMs to both underpin as evaluate the various underlying processes in the model. In terms of evaluation, historical processes may provide a notion of "slow" or "fast" change for the projected rates of change in 2°C pathways. Two approaches can be distinguished that devise history as a reference:

1) **Qualitative comparison by historical analogy:** a first step to evaluating 2°C pathways may be considered in finding analogous examples in the real and past world as a first indicator to confirm or disprove model-based insights (Risbey et al., 1996). Memorable incidences (e.g. the collapse of the Soviet Union) or deducted universal behavioural patterns (e.g. for technology diffusion and growth rates) can be considered important tools to generate insights and draw lessons from past experience (Fouquet and Pearson, 2012; Höök et al., 2012; Iyer et al., 2015; Smil, 2000).

2) **Quantitative comparison to historical reference:** Several comparative studies have related future rates of technological change projected by IAMs to historically observed rates of technological change as a measure for proven achievable change. For example, studies have looked into the difference between future and historical rates of change in absolute values (Kramer and Haigh, 2009; van der Zwaan et al., 2013), as well as relative rates of change (Kramer and Haigh, 2009; Loftus et al., 2015; Wilson et al., 2012). Alternatively, historical trends have also been devised to validate the general behaviour of models by comparing projections after some years against actual developments (Metayer et al., 2015; van Vuuren and O'Neill, 2006; van Vuuren and Riahi, 2008).

1.5.2 Using the expert knowledge lens

Integrated assessment models are used by researchers to develop policy insights, though by inviting in external experts and stakeholders into the modelling process it can be considered an important method for quality control (Van der Sluijs, 2002). Engaging with relevant stakeholders can, for example, reveal errors in the scenario logic or illuminate important social values or disputes, which may attribute to more appropriate levels of analysis and therefore enhance the usefulness of IAMs and their projections on long-term future change. Two approaches can be distinguished that utilise expert knowledge in forward-looking analysis:

3) **Qualitative expert knowledge:** Knowledge of non-scientific (public) stakeholders, denoted as extended peer review by Refsgaard et al. (2007), may contribute to better (1) problem formulations, (2) insights on local knowledge and conditions, and the (3) representation of moral and ethical values in modelling frameworks which create more realistic representations of future change (Refsgaard et al., 2007). Stakeholder engagement may thus reveal alternative pathways for analysis. For example, Schmid and Knopf (2012) demonstrate an iterative process of dialogues in which several civil society stakeholders have been asked to frame the boundary conditions for quantitative models and evaluate the scenarios on their plausibility and social acceptance implications. Other studies have also considered elicitation

protocols to draw insights on the most important driving factors or barriers of change (Vaughan and Gough, 2016).

4) **Quantitative expert knowledge:** An alternative approach to gaining insights in the speed and depth of future change is to gather the opinions of well-informed experts in the field of current and future technological developments. Several forward-looking studies, for example, use expert elicitation as a research tool to assess the influence of various exogenous and endogenous factors on the diffusion of energy technologies. Generally these expert elicitations have focussed on costs parameters (input parameter to models) of single technologies (see for example the elicitations on biomass energy (Fiorese et al., 2014), solar PV (Bosetti et al., 2012), nuclear energy (Anadón et al., 2012), and CCS (Chan et al., 2011) technologies).

1.5.3 Evaluating and expanding the Integrated Assessment Modelling lens

Integrated assessment modelling is an attempt to combine information, analysis and insights from various research disciplines into a functional modelling framework. In that light two modes of integrated assessment can be distinguished:

5) **Single framework studies:** Integrated assessment models are tools with a long-run history in integrating various types of research into a single numerical model. Various IAMs have been developed independently over time. The evaluation of a single existing framework is associated with testing the adequacy of the model, which considers the saliency of the embedded contingencies, biases and uncertainties to the presented outcomes. Several approaches are available to reveal the models' fingerprint, such as sensitivity analysis, probability-based methods or scenario analysis (van Asselt and Rotmans, 2002; Wilson et al., 2017).

6) **Extended framework studies:** A single modelling framework may not be fully equipped to provide a holistic answer to the questions posed, given the wide range of uncertainties about future developments and limitations in quantitative modelling. As integrated assessment modelling by definition is an attempt to unify information, analysis and insights from various research disciplines into a functional model, this leads to two methods for extending the scope of research:

a. *Evaluating with similar disciplinary philosophies and methods*: In the integrated assessment modelling community it has become common to test the robustness of (2°C) pathways in a so-called multi-model inter-comparison (MIP) study. MIPs are a means to include all the considered epistemic uncertainties and different model perspectives into a single exercise. Outcomes that remain rather similar under a cross-model comparison are considered as more robust (Tavoni et al., 2015; Wilson et al., 2017).

Alternatively, as IAMs generally have a limited disciplinary, technological, sectoral, spatial and temporal resolution, more detail could be acquired by linking the computational exercise to more dedicated models (Trutnevyte et al., 2014). For example, economy-energy-environment (IAM) models have been linked to models developed by the climate modelling community and the Impacts, Adaptation and Vulnerability (IAV) community (O'Neill et al., 2014), which can improve our understanding of various processes, implications and feedbacks in the environment and atmosphere. As this type of IAM-extension remains in the physical sciences sphere, it is assumed that such extended modelling endeavours more-or-less adhere to similar philosophies.

b. *Extending with different disciplinary philosophies and methods*: A multitude of blind spots still remain within integrated assessment modelling which predominantly resolve around the disciplines that find no direct analogue to the numerical techno-economic methods as found in IAMs (Risbey et al., 1996; Weyant, 2009). This is particular the case for a wide range of social sciences, despite a growing interest for the implications of behaviour, lifestyle and human interaction over time (Riahi et al., 2015). Several proposals have emerged for extending IAMs with other philosophies and methods, either via alignment (developing a shared problem formulation and framing), bridging (exchange of data and metrics, evaluations of low-carbon innovations, views on promising transition pathways) and iterative interactions between fundamentally different approaches (Turnheim et al., 2015). To a lesser extent more formal modelling attempts of social science conceptualisations have been developed (Li, 2017).

1.6 Thesis outline

The evaluation framework provides the basis of this thesis, for which evaluation methods will be applied selectively to answer the research questions posed in section 1.4 (see also Table 1-1 for an overview). In relation to **research question 1**, this thesis will first assess the range of considered mitigation strategies in line with 2°C on both the global level and the regional level. These 2°C mitigation strategies have been produced within the LIMITS research consortium (Kriegler et al., 2013), a multi-model inter-comparison project analysing the responses of IAMs to projecting transition pathways in line with 2°C under Cancun policy pledges for 2020. In that respect:

Table 1-1 - Overview of used evaluation methods per chapter

		RQ1	RQ2		RQ3		RQ4
ANALYTICAL LENS	**EVALUATION METHOD**	**Ch. 2**	**Ch.3**	**Ch. 4**	**Ch. 5**	**Ch.6**	**Ch.7**
HISTORY	1 Qualitative comparison		•			•	
	2 Quantitative comparison		•			•	
EXPERT	3 Qualitative comparison			•		•	•
	4 Quantitative comparison			•		•	•
IAM	5 Single framework				•	•	
	6 Extended framework	•	•	•	•	•	•

Chapter 2 elaborates on the regional differences found in a multi-model analysis of post-2020 mitigation efforts. Although various other studies have been published prior to this study which looked into regional mitigation efforts with fragmented and delayed mitigation elements (e.g. den Elzen et al. (2010); den Elzen et al. (2011); van Vliet et al. (2012), these have varied in spatial scale and scope. As the diversity in regional resolutions among models and associated studies is considered as one of the major weaknesses in integrated assessment modelling (Clarke et al., 2009; Clarke et al., 2014), this study has compiled and compared an ensemble of IAMs with comparable regional definitions across the models. This chapter zooms in into five regions, for which the global integrated assessment models follow a harmonised set of assumptions on policy developments towards 2020 and beyond.

In relation to **research question 2,** this thesis presents chapters that systematically confront the IAM perspective with other analytical lenses. In that respect:

Chapter 3 systematically compares future patterns of energy system change in 2°C scenarios to historical rates of change. Although history is a common source for the IAM community to gain some indication of plausibility for modelled rates of change (e.g. van Vuuren and O'Neill (2006)), the studies looking into it are hard to compare given different metrics and models being evaluated. For this study, several metrics are selected that represent systems change, which include i) technological expansion rates per annum with specific focus on thermal power technologies and renewable energy technologies, ii) total mitigation costs compared to investment costs, and iii) decarbonisation rates. The outcomes of five IAMs are systematically compared to historical observations of comparable transitions as to draw notions of "fast" and "slow" change for the modelled processes.

Chapter 4 systematically compares future patterns of energy system change in 2°C scenarios to expert projections. Earlier literatures have utilised expert elicitation as a means to extract expectations for technology development over the longer term, though most studies have been limited to single technology studies with an overall focus on the effects to the costs of electricity (Bosetti et al., 2016). In this chapter we introduce an expert elicitation protocol that systematically extracts technology growth and energy system development projections for five technology families in power production from experts, which are then contrasted to IAM projections. Systematic alignments and differences between output from IAMs and experts are discussed based on the findings of this research.

In relation to **research question 3**, this thesis will present chapters that place IAM outcomes in a broader analytical context of future change by considering elements not explicitly accounted for in the modelling framework. In that respect:

IAMs face substantial difficulties in attaining the 2°C target when suboptimal markets and other second-best assumptions are taken into account (Kriegler et al., 2014b; Riahi et al., 2015). This necessitates focussing more on non-economic and non-technological drivers of future change which are only implicitly and stylised represented in IAMs. As a result, **Chapter 5** explores the implications of lifestyle change in 2°C mitigation scenarios using the IMAGE integrated assessment model. This chapter is specifically aimed at addressing a knowledge gap in IAMs by presenting and demonstrating a method to implement greater behavioural realism into scenario-analysis via more specific assumption-based changes to the models' parameterisation.

Chapter 6 builds on chapter 5 by expanding the notion of social actors and behaviour within integrated assessment modelling. This chapter describes a process in which integrated assessment modelling is aligned to more socio-technical transition philosophies and methods to derive an understanding of how a variety of actors can significantly influence the course of change within techno-economic systems analysis. This chapter thus presents an application in which a techno-economic IAM (TIMER/IMAGE) (Van Vuuren, 2007) is combind with a socio-technical transition conceptualisation (Multi-Level Perspective, MLP) (Geels, 2002; Geels and Schot, 2007).

In relation to **research question 4**, this thesis considers whether integrated assessment tools are used as a heuristic instrument to shape policy in line with long-term climate objectives. In that respect:

Chapter 7 provides a comparative analysis of model-based scenario applications and their use in national policy planning. It provides a reflective study that looks into the developments of five Northwestern European countries and considers the value of integrated assessment studies in providing national forward-looking perspective (denoted as ex-ante evaluation).

In the final chapter of the thesis the insights are synthesised to provide conclusive statements for the posed research questions. The thesis ends with final remarks for future research.

Chapter 2

A multi-model analysis of post-2020 mitigation efforts of five major economies

Published article: *van Sluisveld, M.A.E., Gernaat, D.E.H.J., Lucas, P.L., Ashina, S., Calvin, K.V., Garg, A., Isaac, M., Mouratiadou, I., Otto, A.A.C., Rao, S., Shukla, P.R., van Vliet, J., van Vuuren, D.P. (2013) "A multi-model analysis of post-2020 mitigation efforts of five major economies", vol.4, issue 4, Climate Change Economics*

Abstract

This paper looks into the regional mitigation strategies of five major economies (China, EU, India, Japan and USA) in the context of the 2°C target, using a multi-model comparison. In order to stay in line with the 2°C target, a tripling or quadrupling of mitigation ambitions is required in all regions by 2050, employing vigorous decarbonization of the energy supply system and achieving negative emissions during the second half of the century. In all regions looked at, decarbonization of energy supply (and in particular power generation) is more important than reducing energy demand. Some differences in abatement strategies across the regions are projected: In India and the USA the emphasis is on prolonging fossil fuel use by coupling conventional technologies with carbon storage, whereas the other main strategy depicts a shift to carbon-neutral technologies with mostly renewables (China, EU) or nuclear power (Japan). Regions with access to large amounts of biomass, such as the USA, China and the EU, can make a trade-off between energy related emissions and land related emissions, as the use of bioenergy can lead to a net increase in land use emissions. After supply-side changes, the most important abatement strategy focuses on end-use efficiency improvements, leading to considerable emission reductions in both the industry and transport sectors across all regions. Abatement strategies for non-CO_2 emissions and land use emissions are found to have a smaller potential. Inherent model, as well as collective, biases have been observed affecting the regional response strategy or the available reduction potential in specific (end-use) sectors.

Key words: Regional, mitigation efforts, abatement, technological implication, climate policy

2.1 Introduction

In the last few years, the international community has broadly agreed to aim at limiting the increase of global mean temperature to a maximum of 2°C compared to pre-industrial levels (UNFCCC, 2009), although opinions differ on the acceptable level of risks, preferred mitigation strategies and the distribution of costs. Scenario studies indicate that, globally, emission reductions in the order of 35-80% by 2050 are needed in order to be consistent with this target (Rogelj et al., 2011; Van Vuuren and Riahi, 2011). Such reductions cannot be achieved without significant contributions from all major greenhouse gas emitting countries, which raises questions concerning the different emission reduction strategies in major economies (Clarke et al., 2009). So far, most of the literature on scenarios has focused on globally coordinated responses, in particular on the consequences of climate policy at the global level or for large aggregated regions (Van Vuuren et al., 2012). However, the Copenhagen Conference and subsequent UNFCCC dialogues have not led to a comprehensive and long-term multilateral agreement on emission limitation and reduction commitments. Given the present fragmentation in global climate action, the exploration of the role of national strategies across different economies and the implications of delayed global action have become more important (Bertram et al., 2015; Bosetti et al., 2008; Luderer et al., 2016).

This paper presents a comparative analysis focusing on long-term mitigation efforts across five major economies, including the USA, the European Union (EU), Japan, China and India, based on a multi-model scenario analysis oriented towards the 2°C target. The use of multiple models allows us to estimate the robustness of these responses. The analysis discusses two key mitigation scenarios, both starting from a fragmented policy approach, namely the implementation of the national pledges according to the Copenhagen Accords until 2020. The first scenario extends the 2020 pledges by a similar level of ambition in the subsequent decades. The second scenario increases the mitigation ambition after 2020 by assuming a global carbon market aimed at the 2°C climate stabilization target.

The paper is structured as follows: section 2.2 describes the scenario and data used for this study. Section 2.3 discusses scenario results, addressing differences between both scenarios and the models included in the analysis. The focus is on national mitigation efforts, sectoral changes and changes in electricity production. Section 2.4 discusses the results followed by overall conclusions in Section 2.5

2.2 Scenarios and data

The scenarios that are used in this paper are based on different policy assumptions for long-term international climate policy (see Table 2-1) and have been developed as part of the LIMITS project. The baseline (*Base*) scenario addresses the future energy system and emission developments in the absence of climate policy. The fragmented policy scenario (*RefPol*) is based on formulated 2020 national energy and climate targets reflecting the unconditional Copenhagen pledges. The scenario is extended after 2020 by assuming a similar national effort in the subsequent decades (see Table 2-2). Finally, the delayed global cooperation scenario (*RefPol-450*) mimics the *RefPol* scenario until 2020, and thereafter all regions adopt the long-term 2.8 W/m^2 radiative forcing target, consistent with a high likelihood (>70%) of staying within 2^{o}C temperature increase, as a binding commitment for joint mitigation action. Implementation of the target is achieved via a global (harmonized) carbon tax. This scenario can be used to obtain information on attractive strategies at the regional level.

Table 2-1 - Scenario definitions *1

Scenario name	Abbreviation	Explanation
Baseline	Base	No climate policy baseline
Fragmented policy baseline	RefPol	Regional policy reflecting the Copenhagen pledges of individual countries for 2020, and a fixed regional greenhouse gas intensity reduction percentage afterwards based on the current pledges.
Delayed global cooperative action	RefPol-450	Radiative forcing target of 2.8 W/m$_2$ *2 in 2100, with RefPol (fragmented) policy reflecting the Copenhagen pledges of individual countries prior to global cooperation in 2020.

*1 See Kriegler et al., (2013) for a more detailed description of the scenarios.
*2 The policy target assumed for the depicted scenarios refers to the aggregate radiative forcing from the following substances: Kyoto gases (CO_2, CH_4, N_2O, HFCs, PFCs, SF_6), Non-Kyoto gases (substances controlled under the Montreal protocol, i.e. chlorides, halons, bromine; tropospheric and stratospheric ozone; stratospheric water vapor), and aerosols (sulfate, black and organic carbon from fossil fuel and biomass burning, indirect aerosol forcing).

The 2020 targets in the *RefPol* and *RefPol-450* scenarios include capacity and renewable energy share targets as well as greenhouse gas (GHG) emission reduction and intensity targets (see table 2-2). Given the uncertainty in the actual interpretation of the pledges, the targets reflect the lower end of the Copenhagen pledges for plausibility considerations (Kriegler et al., 2013). As such, the European GHG emission reduction target is based on the unconditional pledge of 20% in 2020 relative to 1990 levels, recalculated to reflect 2005 as a base year. Similarly for China and India, who pledged to reduce their emission intensity by respectively a range of 40-45% and 20-25% by 2020 (Townshend et al., 2013), the lower end of their pledge has been included in this study. In the case of Japan the ambition level for GHG emission reductions has been set at the unconditional Kyoto Protocol target (-6%) rather than the conditional Copenhagen target (of -25% relative to 1990 levels) (UNFCCC, 2011) - and has been amended downward to -1% to account for policy changes after the Fukushima incident in 2011[2]. The USA target reflects the general Kyoto Protocol target for industrialized countries. The level of stringency in these 2020 ambitions is extrapolated thereafter until the end of the model time horizon in the form of an annual greenhouse gas intensity reduction rate calculated for Kyoto GHG equivalent emissions including land-use, land-use change and forestry (LULUCF).

Table 2-2 - Regional climate policy targets for RefPol and RefPol-450[*1]

Target in 2020	Unit	China	EU	India	Japan	USA
Across the board GHG emission reduction pledges	% (2005)		-15		-1	-5
GHG intensity reductions	%	40		20		
Modern renewable energy share in electricity production	%	25	20			13
Installed (renewable) energy capacity	GW wind	200		20	5	
	GW solar	50		10	28	
	GW nuclear	41		20		
Average GHG emission intensity improvements after 2020	% /yr	3.3	3	3.3	2.2	2.5

*1 See Kriegler et al., (2013) or the Supplementary Online Material (SOM) for a more detailed description of the policy scenarios.

To get an indication of the robustness of the regional responses we use a multi-model approach, involving seven (global) models (AIM-Enduse: Kainuma et al. (2011) GCAM; Clarke et al. (2007); REMIND: Luderer et al. (2012); MESSAGE: Messner and Strubegger (1995); IMAGE: Bouwman et al. (2006); WITCH: Bosetti et al. (2006); TIAM-ECN: Keppo and Zwaan (2011)) which differ in model characteristics, coverage of sectors, disaggregation and definitions (economy wide or energy system) and baseline assumptions (see Table 2-3). As the sources of key parameters tend to vary (e.g. population and GDP growth projections) this will impact the relative mitigation potential per model (Clapp et al., 2009), but will also allow for the exploration of associated ranges of structural uncertainty and the robustness across a diversity of methodologies (Keppo and Zwaan, 2011). To incorporate outcomes of all models we limit the analysis to 2005-2050 but for models that have a time horizon up to 2100 we extend the timescale for trend analysis of key drivers. When model outcomes overlap we assume modelling consensus, in which case the relative position of individual models is considered less relevant. Clearly deviating model behaviour is seen in 'outlier' values. Results for the world region are included as a weighted average.

2 The policy tendencies after the Fukushima incident are based on calculations from the Japanese National Institute of Environmental Science (NIES) and the Research Institute of Innovative Technology for the Earth (RITE)

Table 2-3 - key model characteristics

Name	Time horizon	Model category	Intertemporal Solution Methodology
AIM-ENDUSE	2050	Partial equilibrium	Recursive dynamic
GCAM	2100	Partial equilibrium	Recursive dynamic
IMAGE	2100	Partial equilibrium	Recursive dynamic
MESSAGE	2100	General equilibrium	Intertemporal optimization
REMIND	2100	General equilibrium	Intertemporal optimization
TIAM-ECN	2100	Partial equilibrium	Intertemporal optimization
WITCH	2100	General equilibrium	Intertemporal optimization

2.3 Results

2.3.1 Mitigation efforts

2.3.1.1 Trends in major drivers of emissions

Population and income are major drivers of CO_2 emission growth in the absence of climate policy. Models differ with respect to population and GDP assumptions as a result of varying statistical data sources, base year and methods for accounting (Chaturvedi et al., 2012), creating a band that can be seen in Figure 2-1a-b. For population, India and the USA show a rapid increase in population size in the 2010-2050 period. After 2050, growth rates in both regions are considerably reduced, resulting in a declining population in all models for India and in diverging trends for the USA. In China and the EU population growth stagnates by 2050, followed by a decline. For Japan, the population is projected to decline in all models throughout the whole century. In China, EU and Japan, the projected 2100 population is below the 2005 level. For income, there is a clear distinction between the developing countries and industrialized regions. The average growth rate for India and China is rapid in the short term (respectively 7-8% and 8-9% per year). In contrast, in the EU, Japan and the USA the growth rate is only 1-2% per year (Figure 2-1b).

It should be noted that socioeconomic trends are exogenous inputs derived from sources independent of the integrated assessment models, hence trends are equal in every scenario and show no relation to the implemented climate policy. MESSAGE is found to adopt both higher relative and absolute values for population in China, EU and India compared to other models, which may have a noticeable effect on the available abatement potential under 2°C constraints. For GDP growth we find IMAGE to be relatively optimistic in both relative and absolute terms for China, EU and India. The implications of this are not clear, since the literature is inconclusive concerning the possible implications of rapid economic development for meeting the radiative forcing target (Van Vuuren et al., 2012).

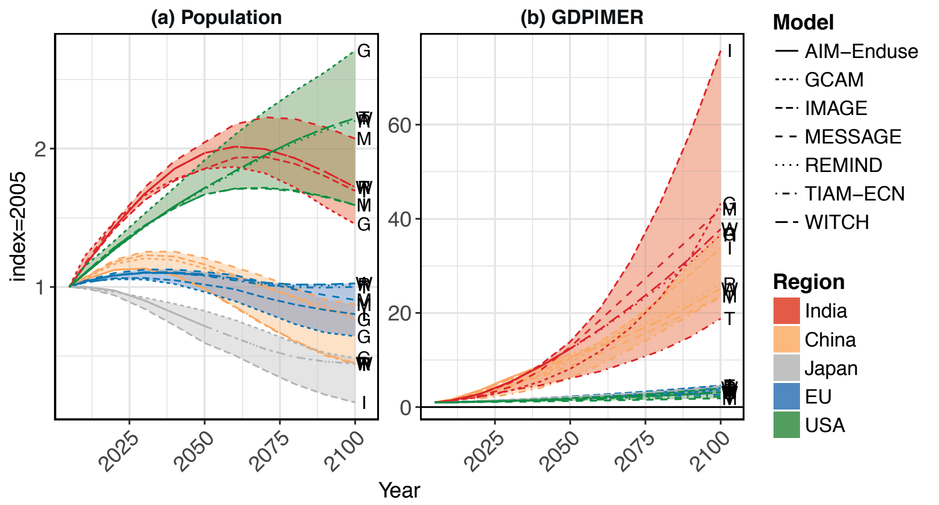


Figure 2-1- (a-b) Indexed growth figures of population and GDP (MER) per capita of all the considered regions.

2.3.1.2 Trends in CO_2 emissions

Figure 2-2 shows the regional emission projections for all three scenarios. Baseline CO_2 emissions are generally projected to gradually increase for all regions and most models show either a peak or stabilization in the second half of the century. Only the WITCH and TIAM-ECN models depict constant growth throughout the century in nearly all regions.

The short term targets included in the *RefPol* scenario (reflecting the Copenhagen pledges) lead to emission reductions compared to the baseline scenario in all regions. The level of emission reduction differs strongly across regions. While in India and China the 2020 commitments lead to noteworthy reductions compared to baseline, emissions are still projected to increase and reach a peak near 2050 in China, and later in India. This is in contrast to the EU, Japan and the USA, for which the Copenhagen commitments are projected to lead to immediate decreasing emission pathways. In fact, the difference between the EU ambition level in the *RefPol* scenario and in the RefPol-450 scenario is small, implying that the assumed policies for the EU in the *RefPol* scenario aim for emission reductions that seem to be in line with the 2°C target (Clapp et al., 2009) .

It should be noted that for China and India the *RefPol-450* emission trajectory peaks immediately after 2020. For the high income regions the *RefPol-450* emissions need to be more than halved by 2050 compared to 2005 levels. All economies and models show that negative emissions are needed near the end of the century to reach the 2°C stabilization target.

As described earlier, the assumptions concerning socioeconomic development are considered to be important drivers of total emissions. However, the results show that clearly deviating assumptions (e.g. population in relative and absolute terms in China for MESSAGE and the USA for GCAM) do not necessarily define the borders of the outcome space but lead to outcomes that remain more or less within the range of future (baseline) emissions. In the reference scenario most regions show a significantly larger range of possible outcomes than in the mitigation scenarios. This is due to the interplay of various fundamental processes and different base-year values for key

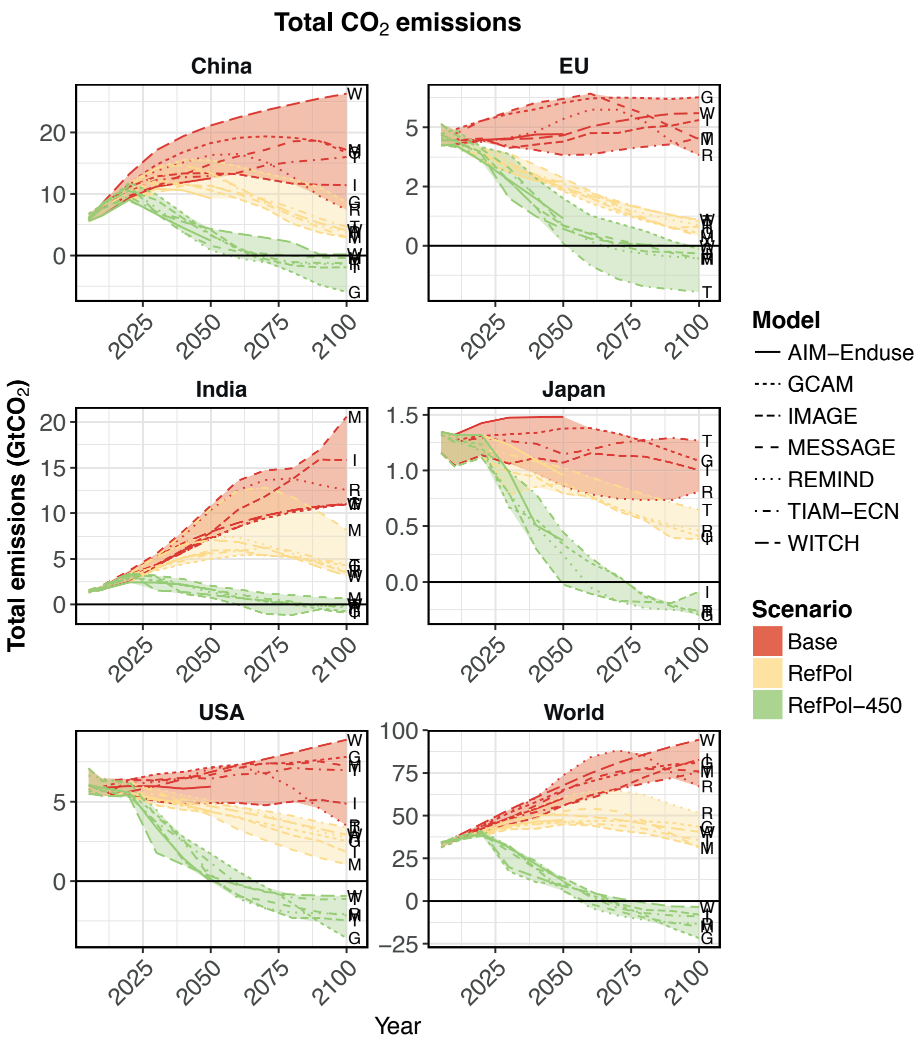


Figure 2-2 – Total CO_2 emission paths of the no policy baseline (red), RefPol (yellow), RefPol-450 (green) scenarios over the 2005-2100 period.

metrics (Chaturvedi et al., 2012; Edenhofer et al., 2010) in the reference scenario and due to the unanimous shift to (vigorous) mitigation options that lower energy demand across all regions (Van Vuuren et al., 2012) in the mitigation scenarios.

In order to achieve the 2°C climate stabilization target a sustained global annual CO_2 emission reduction rate of approximately 2%-5% is required for all regions between 2020 and 2050, which is in contrast to the 1%-2% sustained annual emission reduction rate under *RefPol* circumstances for developed regions and the emission increase in developing regions (see Figure 2-3). Reduction rates of this order are considered as extremely rapid and well beyond rates known in history and require much greater mitigation efforts than projected under current Copenhagen Accord pledges (van Vuuren and Stehfest, 2013). In the USA the relatively rapid increase in population results in a projection that requires greater efforts relative to the *RefPol* scenario. The differences between India and China in Figure 2-3 are related to future projections of rapid economic change and the rate of capital stock turnover in the energy production sector (Lucas et al., 2013).

2.3.2 Emission decomposition

We apply the Kaya-identity (Kaya, 1990) to examine the regional contribution to CO_2 emissions reductions of changes in efficiency and consumption patterns (energy intensity) and of changes in the choice of energy carriers (carbon factor). For further elaboration on the calculation the reader is referred to Steckel et al. (2011); Zhang et al. (2009). It appears that in all regions decarbonization is the leading strategy and the level of climate policy determines to which extent this occurs. However, it should be noted that the emission reductions shown in Figure 2-4 are relative to the no policy baseline scenario, which implicitly entails some bias as the reference scenario encompasses a degree of autonomous efficiency improvements whereas the carbon factor remains unchanged. In India and China the reduction of emissions through energy efficiency is projected to play a larger role. This can be explained by looking at the absolute values for carbon intensity and energy intensity. The data show that in 2050 the carbon intensity is at a similar level for all regions (near 60 kg/GJ), whereas the energy intensity can still be reduced by a factor of 4-6 in the developing regions.

Another type of bias can be observed in the model types present in this study, as earlier studies (Johansson et al., 2012; van Vuuren et al., 2009) argue that CGE/econometric models (top-down) show more demand side changes than energy-system models (bottom-up) and therefore favour energy savings. In this study this tendency is apparent as well since the WITCH model (a hybrid energy system and economic growth model) shows a greater preference for energy efficiency solutions (particularly in China, as shown

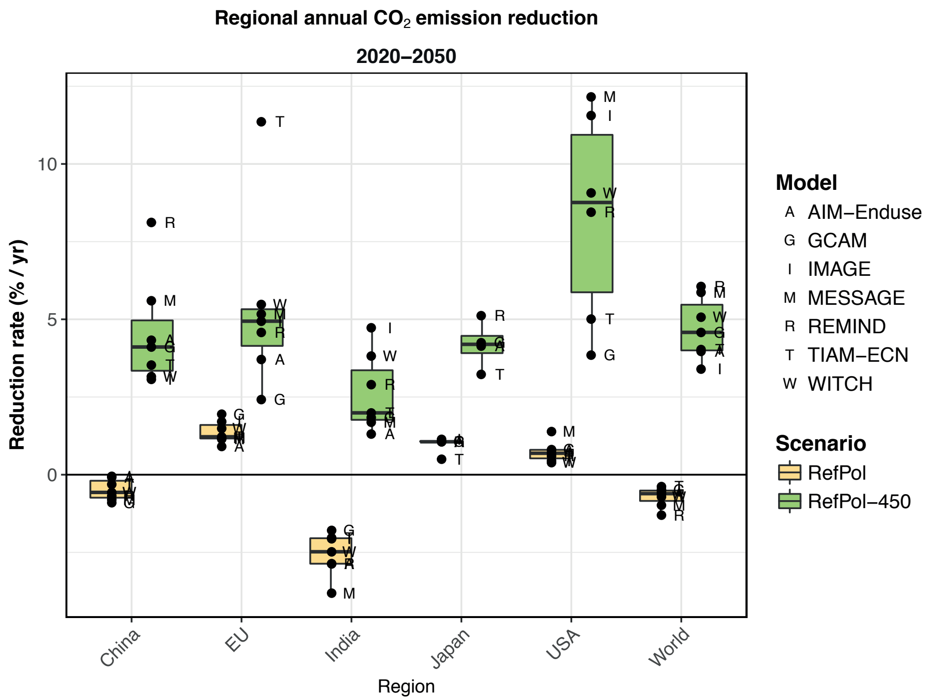


Figure 2-3 - Average CO_2 emission reduction rate per year between 2020-2050 (relative to 2005 levels). Negative CO_2 emission reductions indicate emission growth.

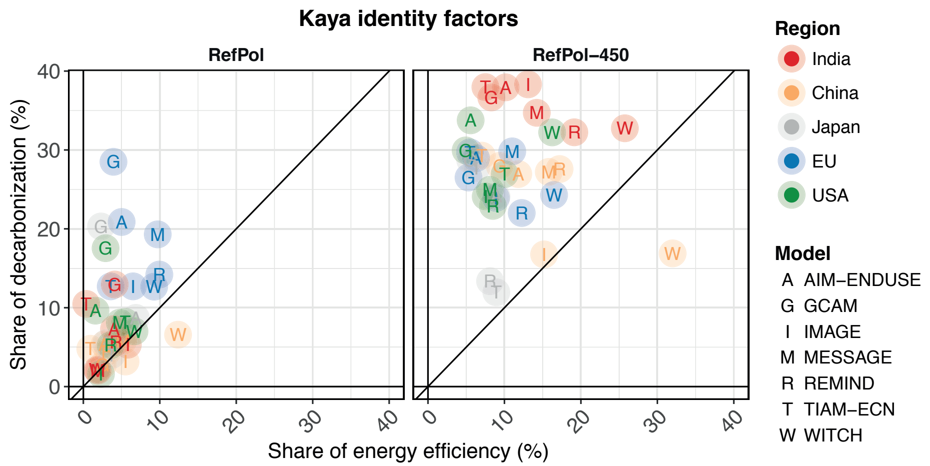


Figure 2-4 – Decomposition of regional emission reductions relative to Base emissions, axes depict the share of a strategy in total emission reductions between 2005-2050 for the RefPol and RefPol-450 approach.

in Figure 2-4), whereas more strongly technology based (bottom-up) models (such as AIM-Enduse, GCAM and TIAM-ECN) generally show more carbon intensity reductions.

2.3.3 Sectoral emission changes

By zooming in to the sectoral level (Figure 2-5), it can be observed that the energy production sector (or power sector, combining power and heat supply, extraction, transformation and distribution) is projected to contribute the most to emission reductions in all regions and models in a 2°C regime, which can be explained by the large amount of greenhouse gas emissions for this sector, the relatively large potential for emission reduction (including technologies such as Carbon Capture and Storage (CCS), nuclear power and renewables) and the possibility for 'negative emissions' (through combining biofuels with CCS) (Hallding, 2011; van Vuuren et al., 2009). For the EU, models agree that the additional emission reductions in the energy production sector are limited as projections of Copenhagen or 2°C ambitions show similar emission reductions in this sector in the short term. In contrast, the emission reduction in emerging regions such as China and India is larger as 2°C ambitions diverge from the reference scenario to a greater extent. A considerable spread in outcomes can be seen across the models, yet models that project higher baseline emissions (Figure 2-2) consistently report higher emission reductions as well (e.g. WITCH and REMIND).

Changes in the demand sectors (including industry, transport, residential and commercial and other sectors) typically contribute 10-20% of total emission reductions in the *RefPol-450* scenario. No systematic differences in reduction percentages across the different regions can be observed (despite the expectation of higher reduction rates in India and China as a result of reportedly lower levels of end-use efficiency). In the results, some differences between the models can be noted, with relatively high reduction rates in MESSAGE and AIM-Enduse, possibly caused by greater detail in end-use sector systematics in these models. In GCAM and REMIND relatively lower rates are observed, which is partly due to higher decarbonization rates in the energy production (both REMIND and GCAM) and land use (GCAM) sectors, reducing the relative contribution of the end-use sector in the mitigation strategy.

Not all models report emission reductions from land use, land-use change and forestry (LULUCF) measures (GCAM alone reports consistently LULUCF emission reductions for each region). The results suggest a limited abatement potential, i.e. up to 10% emission reduction relative to cumulative baseline emissions for both climate policy scenarios. In fact, the contribution of this category is lower in the *RefPol-450* scenario than in the *RefPol* scenario, showing that emission savings from LULUCF measures might be offset by the increasing need for bioenergy and CCS under strict climate policies (Calvin et

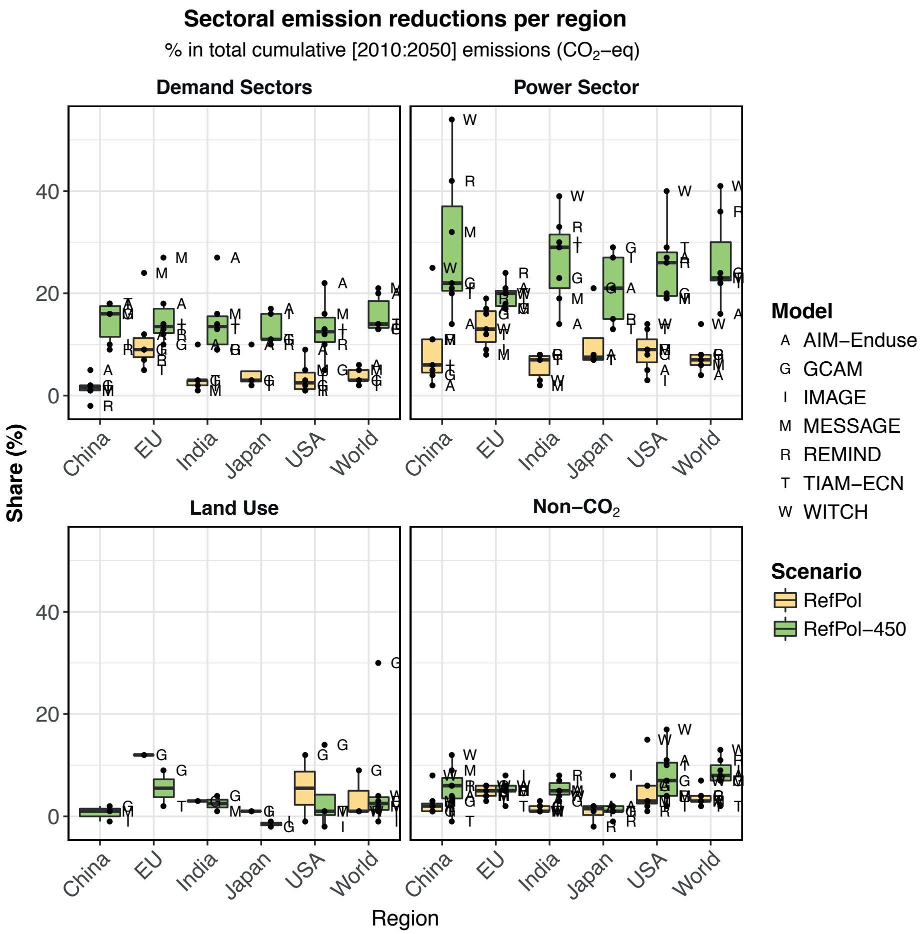


Figure 2-5 - Reduction percentage of cumulative emissions between 2005 and 2050 for the RefPol and RefPol-450 scenarios, compared to the baseline scenario in different sectors.
The power sector covers CO_2 emissions from power and heat generation, other energy conversion (e.g. refineries, synfuel production), resource extraction and energy transmission and distribution (e.g. gas pipelines). The demand sectors encompass the industry, residential and commercial, transportation and other sectors. Land-use encompasses net carbon dioxide emissions from all categories of land use and land-use change (e.g. pasture conversion, deforestation, afforestation, reforestation, soil management, etc.). Non-CO_2 emissions encompass residual Kyoto gas emissions (CH_4, N_2O and F-gases) of all the former described sectors.

al., 2013; Wise et al., 2009). GCAM's greater projected LULUCF abatement potential in the EU and USA is directly linked to the explicit implemented policies that incentivize afforestation. For Japan, the potential for emission reductions from land-use change and forestry is argued to be too low to justify developing explicit abatement policies (OECD, 2010).

Non-CO_2 sources, although considered a relatively important short to medium term mitigation option (den Elzen et al., 2008; Lucas et al., 2007; Rao and Riahi, 2006), appear to have limited abatement potential for all regions by 2050, ranging around 5-10% of total cumulative emission reductions relative to the baseline. China, India and the USA show the largest greenhouse gas abatement potential through non-CO_2 emission reductions, whereas the non-CO_2 abatement potential is considered negligible for Japan.

Looking at emission reductions in subsectors of the demand sector, we observe that the industry sector (including feedstocks, agriculture and fishery) is the main source for abatement in China and India, whereas the USA and the EU achieve significant emission reductions through measures in the transport sector (see Figure 2-6). Japan forms an exception among developed regions, which could be explained by the high level of energy efficiency already implemented in the Japanese transport sector (Lipscy and Schipper, 2013). Transportation abatement is smaller in GCAM than in other models due to the abundance of other low cost mitigation measures (e.g. LULUCF, bioenergy with CCS). In all regions, as the contribution of industry to total end-use sector emission reduction increases, emission reductions from other end-use sectors become less important. The residential and commercial sector shows a marginal contribution to the regional abatement potential for all regions, except for a single result by TIAM-ECN for China.

2.3.4 Changes in electricity production

In the previous section, in all regions the energy supply sector is shown to have the largest potential for emission reductions. Here, we examine the changes in electricity production in detail. Figure 2-7 shows the percentage of electricity production from different electricity generation technologies in 2050 in specific regions for the two mitigation scenarios. Several regional patterns can be identified in Figure 2-7:

- In terms of coal-based electricity production, the Chinese and Indian regions show the largest fraction of coal energy use in *RefPol*, due to the large available reserves (Garg and Shukla, 2009; Hallding, 2011; Shukla and Chaturvedi, 2012). Coal also makes a substantial contribution to electricity production in Japan and the USA in the *RefPol* scenario but with considerable spread across the models. The EU generally has a lower fraction of coal and a higher fraction of natural gas and nuclear electricity (but with little consensus among the various models). The *RefPol-450* scenario shows that, with the introduction of a global carbon tax, coal-based electricity production decreases drastically over time regardless of the model or region.

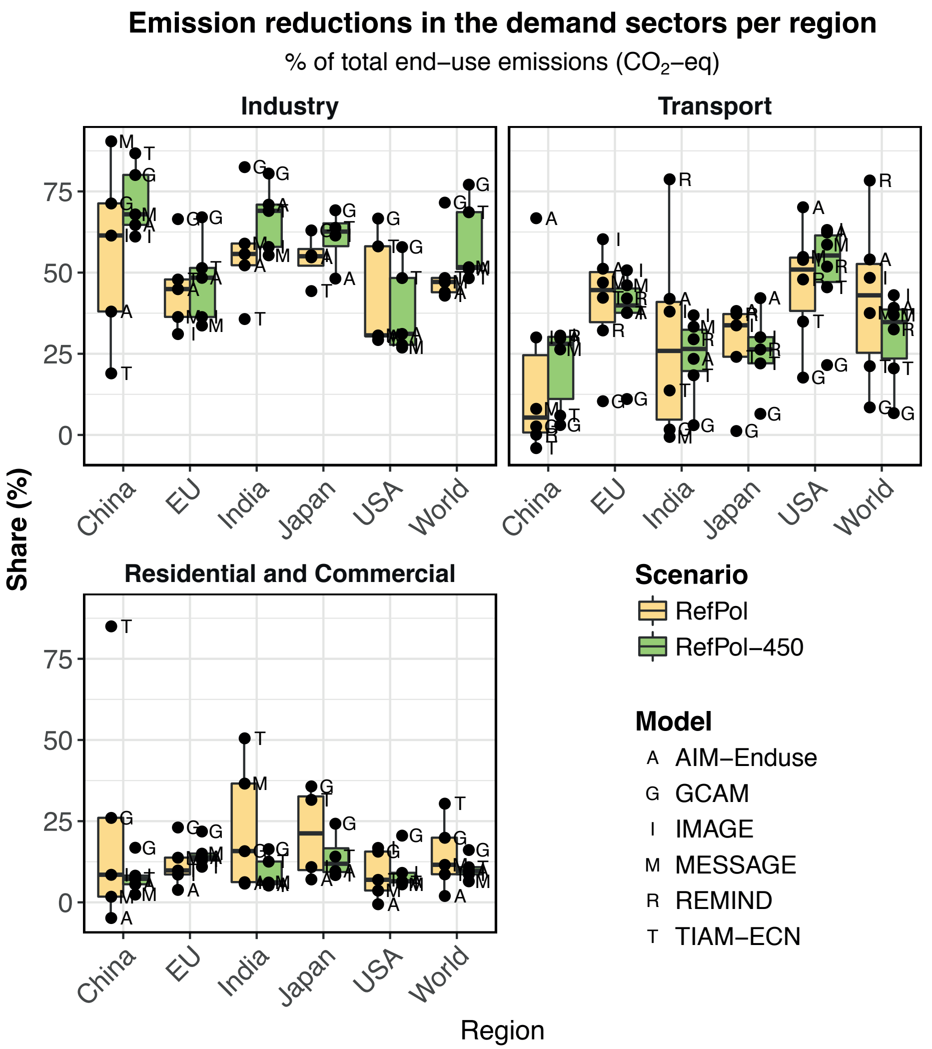


Figure 2-6 – Emission reduction shares per end-use-sector, reductions are relative to total end-use abatement potential compared to baseline emission reductions (indicating relative importance of the abatement potential of a sector within the aggregated energy end use category)

- Natural gas plays a key role in the power systems of the USA and Japan and to some degree in the other three regions in the *RefPol* scenario. This contribution is significantly reduced in the 2°C scenario and is eventually to be phased out, albeit later than coal, at the end of the century.

- Fossil fuels combined with CCS technologies are important in most regions, particularly coal w/CCS in India, for which the bandwidth of reported model

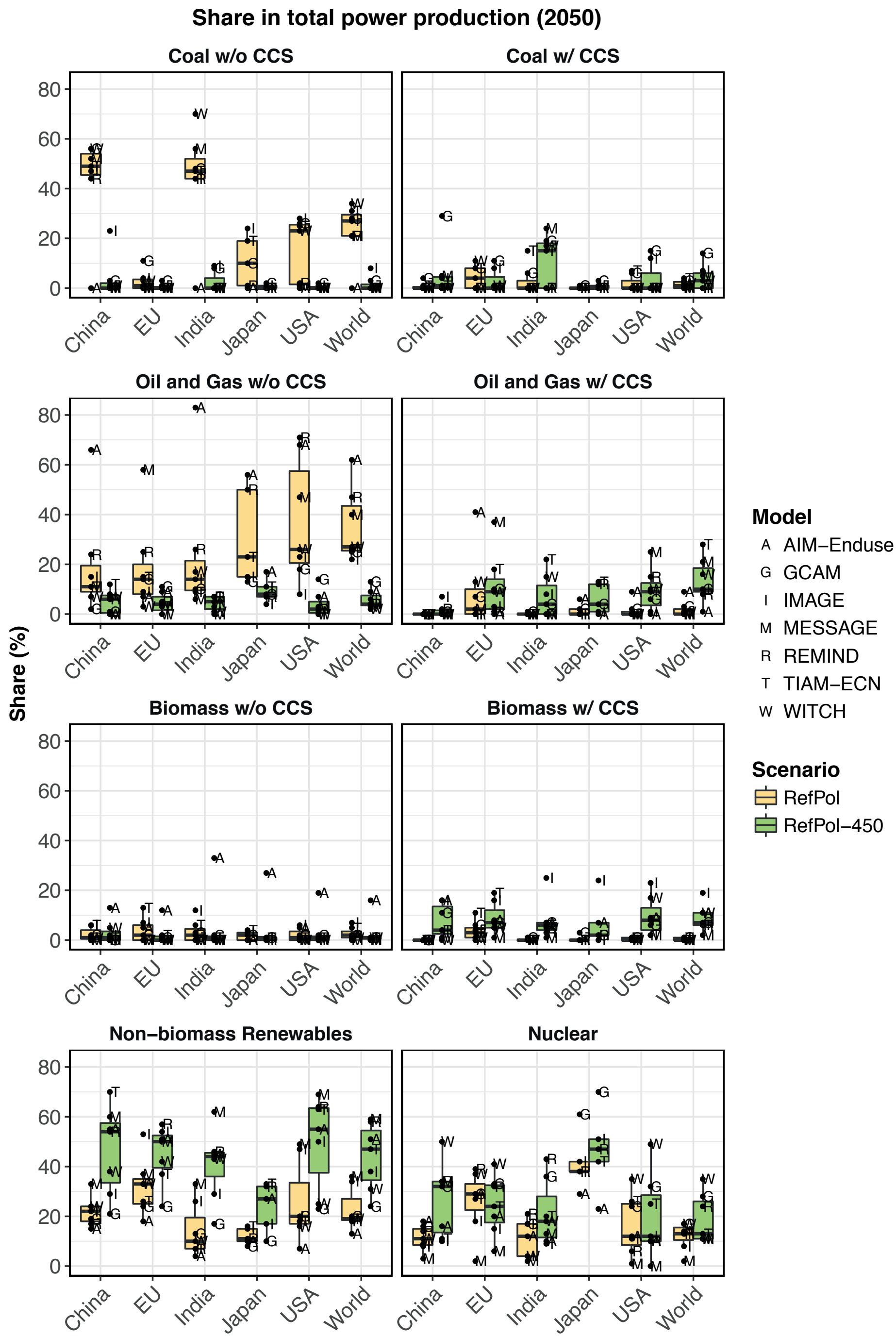


Figure 2-7: Share in total power production per energy technology for major and upcoming regions in 2050 in the *RefPol* and *Refpol-450* scenario (Non-biomass Renewables: PV, CSP (concentrated solar power), on- and offshore wind and hydropower; CCS: Carbon Capture and Storage)

outcomes is relatively small, thus implying modelling consensus. For China, however, only GCAM reports a high share of coal w/CCS compared to other models, which can be explained by the high capture rates assumed in the model. In the *RefPol* scenario, CCS technology is almost exclusively used in the EU as in other regions the policies are seemingly not ambitious enough to make CCS attractive. The use of biomass for electricity production without CCS is limited for most regions, but is more commonly applied in combination with CCS (BECCS) in all regions and all models in the case of the 2°C scenario. Shares of BECCS are higher in USA, China and the EU, most likely because these regions have better access to biomass feedstock.

- No clear transition strategy can be extracted from the renewable energy production and nuclear energy use plots as there is a high diversity in model outcomes for low-carbon and clean energy technology deployment (see also van der Zwaan et al. (2013)). However, nearly all regions show a 2-3 fold increase of the (non-biomass) renewable energy share in electricity production. Nuclear energy use increases on average, but more conservatively for all regions except China, hence making it an important technology towards a 2˚C transition. Consensus exists for Japan, showing greater dependence on nuclear energy production due to limited renewable energy potential, implying limited alteration in the national strategic energy plan of Japan as designed prior to the Fukushima nuclear incident.

In general it can be concluded that in the *RefPol* scenario, in 2050, the electricity system in China and India will rely mostly on coal and gas, therefore leading to a higher carbon content in electricity for these regions; whereas the electricity mix in the EU, USA and Japan has shifted to a greater reliance on nuclear and non-biomass renewable energy. If the 2˚C climate stabilization target is to be achieved, China's and India's electricity system must urgently start to shift away from a coal dependency, albeit with differences in transition strategies. In the projections India employs CCS to prolong fossil fuel use, whereas China replaces coal with alternative carbon-neutral and carbon removal technologies. For other, developed, regions, a greater effort is required to stay in line with the 2˚C climate stabilization target, which will be further discussed in the next paragraph.

2.4 Discussion

Integrated assessment models are useful tools to help understand the consequences of decision-makers' actions, through providing quantitative information about possible pathways for economic, social and environmental developments under different circumstances. In this study, the designed scenarios have been based on formulated 2020 national energy and climate targets, reflecting unconditional Copenhagen pledges or amended Copenhagen pledges to account for restraining occurrences in specific regions. In order to look further into the consequences of current 2020 commitments, we consider a limited set of policy relevant indicators to discuss the projected and required regional mitigation efforts (see Table 2-4):

- For Europe, the reference scenario includes the targets of 20% emission reductions, 20% share of renewable energy and 20% more energy efficiency by 2020 (relative to 1990 levels, as part of the Europe 2020 strategy) (see also OECD/IEA (2012)). This strategy implies an annual emission reduction rate of 1-2% till 2020. However this commitment, or the continuation of such rate of change after 2020, shows to be insufficient as a 2-11% emission reduction per annum is more likely to stay in line with 2°C ambitions. Moreover, energy efficiency needs to improve at a faster rate while doubling the 2020 renewable energy deployment rate by 2050.

- In the US, several sectoral and state level policies have currently been implemented (such as regional cap-and-trade programs, renewable portfolio standards and, to a smaller degree, feed-in tariffs at a state level) yet a long-term (federal) commitment is missing (Schuman and Lin, 2012). In the reference scenario this translates to an emission reduction of around 1% per annum till 2020. In a 2°C scenario this requires a much higher annual emission reduction rate (of 4-12% per year depending on the model) in subsequent years till 2050. Some models even suggest lower per capita emissions for the USA than in other OECD regions in 2050, which can be attributed to the considered potential for CCS, renewable energy and bio-energy (especially CCS use is much higher than in other regions).

- As Japan has formally committed itself to a conditional pledge of 25% of emission reductions relative to 2005 (conditional to the participation of all major economies) (UNFCCC, 2011), a consistent annual emission reduction rate of 2% would be minimally required to comply to this 2020 target. Although this rate is much higher than currently assumed in the reference scenario (accounting for possible revised nuclear policies in Japan), it still shows to be misaligned with 2°C ambitions. After 2020, a more rapid annual decrease in emissions is required regardless of the considered commitment. Furthermore, the results also suggest that nuclear power will play a significant role in reducing emissions in Japan. However, since the Fukushima accident, several initiatives to reduce the reliance on nuclear energy have been proposed (e.g. achieved through more renewable energy, greater energy efficiency improvements, reforms in energy systems and a (restrained) increase in fossil-fuel generated energy) which may lead to the sacrifice of nationally pledged climate change goals (National Policy Unit, 2013). The combination of both an

Table 2-4– Quantitative overview table of the median and the bandwidth of modelled regional outcomes

Policy relevance	Scenario	Unit	China	EU	India	Japan	USA
GHG emission reduction relative to 2005	RefPol	%2030	-88 (-127 - -63)	25 (22-29)	-129 (-218 - -108)	13 (7-39)	11 (10-20)
		%2050	-79 (-103 - -52)	44 (35-47)	-243 (-334 - -174)	31 (28-33)	22 (18-38)
	RefPol-450	%2030	-14 (-41 - -8)	33 (17-49)	-63 (-87 - -20)	33(25-48)	37 (26-64)
		%2050	45 (25-72)	74 (51-77)	-15 (-56-30)	74 (69-96)	86 (61-90)
GHG emission intensity relative to 2005	RefPol	%2030	38 (32-66)	62 (57-79)	46 (36-57)	76 (62-89)	64 (57-70)
		%2050	23 (20-33)	50 (42-66)	25 (22-44)	59 (45-68)	47 (38-51)
	RefPol-450	%2030	27 (23-57)	58 (47-78)	35 (27-51)	70 (53-84)	55 (43-67)
		%2050	17 (12-29)	47 (30-61)	21 (11-38)	54 (37-60)	40 (26-46)
Per capita CO_2 emissions	RefPol	tCO_2/cap2030	8.4 (6.2-10.1)	6.2 (5.8-6.8)	2.6 (2.5-3.4)	9 (6-10)	14 (13-16)
		tCO_2/cap2050	9 (7-10)	5 (4-5)	4 (3-5)	8 (8-9)	11 (9-13)
	RefPol-450	tCO_2/cap2030	5.1 (4.1-6.3)	5.2 (3.8-6.4)	1.7 (1.0-2.0)	6.8 (5.4-8.3)	9.8 (4.9-12.3)
		tCO_2/cap2050	2.2 (0.7-3.3)	1.6 (0.1-3.4)	0.9 (0.5-1.1)	2.9 (-0.2 – 4.1)	0.8 (-0.1 – 3.9)
Average annual CO_2 reduction rate 2020-2050	RefPol	%	-1 (-1-0)	1 (1-2)	-2 (-4- -2)	1	-1 (-1 – 0)
	RefPol-450	%	4 (3-8)	5 (2-11)	2 (1-5)	4 (3-5)	9 (4-12)
Peak year emissions	RefPol	Mt CO_2eq	2030-2045	<2005	2045-2070	<2005-2020	<2005
	RefPol-450	Mt CO_2eq	2020	<2005	2020	<2005-2020	<2005
Negative GHG emissions	RefPol	Mt CO_2eq	>2100	>2100	>2100	>2100	>2100
	RefPol-450	Mt CO_2eq	2080->2100	2100	2070->2100	2060-2080	2060-2080
Year of CCS application	RefPol	Year	2030-2070	2020-2035	2030-2070	2020-2050	2020-2050
	RefPol-450	Year	2020-2070	2020-2025	2020-2025	2025	2020-2025
Share of non-biomass renewable energy in electricity production	RefPol	%2030	22 (19-28)	40 (26-47)	12 (6-19)	15 (9-15)	14 (6-30)
		%2050	22 (15-33)	33 (18-53)	10 (4-33)	13 (8-16)	20 (7-49)
	RefPol-450	%2030	30 (26-38)	40 (28-47)	20 (15-37)	16 (11-27)	25 (18-38)
		%2050	54 (21-70)	50 (24-57)	44 (17-62)	29 (10-33)	55 (23-69)

Table 2-4– Quantitative overview table of the median and the bandwidth of modelled regional outcomes (continued)

Policy relevance	Scenario	Unit	China	EU	India	Japan	USA
Share of CCS in total fossil fuels and industry CO_2 emissions	RefPol	%2030	0	1 (0-4)	0 (0-1)	0 (0-1)	0 (0-2)
		%2050	3 (0-6)	20 (15-26)	1 (0-10)	1 (0-9)	5 (0-10)
	RefPol-450	%2030	2 (0-6)	6 (2-17)	6 (2-37)	2 (1-5)	4 (3-27)
		%2050	49 (0-65)	47 (36-91)	47 (5-78)	35 (23-82)	78 (44-103)
Share of Nuclear energy in electricity production	RefPol	%2030	6 (5-9)	23 (19-27)	7 (3-10)	31 (26-55)	17 (10-27)
		%2050	10 (3-16)	29 (2-39)	12 (2-21)	38 (29-62)	12 (1-35)
	RefPol-450	%2030	13 (9-33)	24 (15-40)	12 (8-23)	36 (27-57)	21 (11-54)
		%2050	33 (10-50)	24 (6-41)	18 (9-43)	44 (23-70)	12 (0-49)

2

inadequate emission reduction commitment and a diverging mitigation strategy may thus lead to a bigger post-2020 challenge for Japan than currently anticipated.

- In the 2°C scenario, Chinese emissions would more-or-less peak in 2020 followed by a decline. In order to follow this pathway, China needs to maintain a similar annual emission intensity reduction rate of 4% as committed to in the Copenhagen pledges and extend this rate till 2050. This requires a major energy transition, surpassing the non-hydro renewables generation of regions like the USA and EU by 2025-2030 to fulfil its future energy demand.

- A similar pattern is observed for India, as emissions are projected to peak and decline in the first half of the century while returning to 2005 emission levels no sooner than 2050 in the 2°C scenario. However, unlike China, current efforts are found to be inconsistent with 2°C ambitions, as the emission intensity improvement committed to in the Copenhagen Accord is slightly below the value that is needed (currently describing a constant annual emission intensity reduction of 2.9% till 2020, whereas at least 3.4% is needed till 2050). As less 'easy' reduction options will be available and increasing economic growth is expected, this will represent a clear challenge for India. Moreover, per capita emissions in India are projected to remain significantly below the OECD average (which could be very important in the context of proposals on emission allocation and financing).

Table 2-4 thus emphasizes that significant emission reductions are needed in all regions, yet more rapid changes than currently described in the Copenhagen commitments are required per region. For the three high-income regions this implies that emissions need to be reduced more rapidly than accounted for in the 2020 commitments, whereas a turnaround in emission trajectories and faster decarbonization rates are required for China and India. Lastly, it should be noted that some evidence in earlier studies suggest that global assessment models are more optimistic about emission reductions and technological developments than national models (either due to better representation of national policies or assumed higher economic growth), possibly implying even greater regional challenges than described in this paper (Chen et al., 2016; Johansson et al., 2012; Yang et al., 2011).

2.4.1 Policy consequences of current model projections

Another policy implication relates to the wide variation in the future portfolio choice among nuclear, CCS and non-biomass renewables across the models. For example, models that assume a greater scope for bioenergy, or the combination of bioenergy and CCS, allow regions with high application rates (such as the USA and EU) to rely heavily on the assumed technologies. As negative emission technologies will specifically play a key role in the second half of the century (considering how net negative emissions will be achieved in the 2060-2080 period in developed regions and no sooner than 2080-2100 in developing regions), it implies that global and local decisions made today will partly be based on our expectations of long-term technology developments over multiple decades.

Other factors that are not explicitly modelled may also influence the choices for available future energy portfolios, such as technological constraints, geopolitical limitations and suboptimal policies. For example, the depicted rapid growth in renewable energy production in the scenarios (45-55% by 2050 relative to 2005 across every region except Japan) will be very challenging in all regions given the intermittency of these resources, but even more so in developing regions due to the poor current infrastructure, the slower market signals and lack of conducive renewable energy push policies (Hong et al., 2013; Shukla et al., 2007; Shukla and Chaturvedi, 2013). Interesting in this context are also the expectations on economic growth. Economic stagnation may dampen the available resources and thus endanger the continuity of policies, creating suboptimal policies in the long run. The European Union, for instance, suffers from the impact of the economic crisis on the emission trading scheme, and has also abandoned subsidy programs and postponed planned investments in long-term infrastructure (Townshend et al., 2013). The effect of inconsistencies in climate mitigation policies has also been particularly critical for the renewable technology investment climate in the USA, causing boom and bust cycles over time (OECD/IEA, 2012).

2.5 Conclusions

In this paper we have identified trends in region specific responses to climate policy by looking at the results of a multi-model scenario study. The analysis is based on (1) a reference scenario assuming policy implementation of Copenhagen Accord pledges followed by similar mitigation action after 2020 and (2) a scenario that assumes strengthening of regional action after 2020 in order to reach the 2°C target (assuming an international carbon market). The main conclusions of this analysis are:

Optimal reduction pathways leading to the achievement of the 2°C target require greater energy system transformations compared to current policies in all regions after 2020.

The results indicate that without more stringent climate policy emissions in the assessed regions will not stay in line with the 2°C climate stabilization target. Emissions in India and China are projected to rise under unilateral climate ambitions, with an energy-related $CO_{2\text{-eq}}$ emissions peak arriving no sooner than 2030. Due to the accelerating growth in socioeconomic indicators, developing regions face increasingly greater challenges over time. While the reference scenario in the EU, based on the pledged targets, leads to considerable emission reductions close in line with 2°C ambitions, further reaching reduction commitments are needed. In order to stay in line with the 2°C regime, the EU will be required to at least double its 2020 commitments in terms of renewable energy capacity by 2050. In the USA, as well as Japan, the rate of emission reduction in the reference scenario is lower than 1% per annum till 2020. For both regions this means that more rapid reductions are required in a 2°C regime after 2020 to compare to at least similar per capita levels as in Europe under increasing socioeconomic trends (USA) or to correct for possible changes to be made in the mitigation strategy (Japan).

Both similarities and differences in mitigation strategies are observed for all regions. Putting in place a 2°C global climate stabilization target leads to an immediate inflection point in emission trajectories. Such a target requires a tripling or quadrupling of currently pledged mitigation efforts across each region. The results show that most emission reductions come from decarbonization of the energy supply sector in all regions and from the deployment of technologies with negative emissions in the second half of the century.

The most important response strategy observed in this study is the shift away from fossil-fuelled power plants without CCS towards renewable energy and carbon-neutral sources. This shift in energy production leads to a diversification of the energy supply sector in all regions, with some differences in terms of mitigation strategy per region. Two specific directions become apparent, namely prolonging fossil fuel consumption by coupling conventional methods with carbon storage technologies (India, USA) and rigorously shifting to carbon-neutral technologies with mostly renewable (China, EU) or nuclear power (Japan). Regions with access to large amounts of biomass, such as the USA, China and the EU, can make a trade-off between energy related emissions and land related emissions, as the use of bioenergy can lead to a net increase in land use emissions. Japan shows a distinct preference for the expansion of nuclear power generation as its main mitigation strategy, despite the current reduced social acceptance of nuclear power accounted for in this study. This result is mainly due to supply constraints of other sources in the country. All regions are found to require power generation from all available renewable sources to fulfil future energy demand while substituting for conventional fossil fuelled power generation. In China, the expansion of renewable energy is very rapid and the countries' deployment rate is projected to surpass those of the USA and EU by 2025-2030. More stringent ambitions appear to extend the response capacity of the regions, rather than lead to deviating mitigation strategies.

The next most important abatement strategy is energy efficiency in end-use sectors, leading to considerable and more-or-less homogeneous emission reductions across all regions. Other mitigation strategies focusing on non-CO_2 emissions and land use emission can be considered as complementary response strategies as they contribute only marginally to the total emissions reductions for each region.

Models may show a tendency to favour a specific transition strategy in all regions.
In this study we used multiple models to examine regional response strategies. The results highlight the importance of the underlying assumptions and structure of each model. It can be seen that models have a tendency to favour specific response strategies in all regions, due to (1) their baseline assumptions (higher baseline emissions tend to result in more emission reductions being needed), (2) the model structure (which influences the level of decarbonization or efficiency improvement that can be achieved) or (3) the assumptions on technology developments (as models assuming a greater scope for specific technologies also project a greater reliance on the assumed technologies). Model comparison studies can expose these biases, but it should be noted that there can also be collective biases, for instance, in the abundance of lower cost mitigation measures in the energy supply sector, underestimating the available abatement potential in specific (end-use) sectors such as industry or transport.

Further in-depth research is recommended into the implications of inherent model differences, uncertainties and underlying assumptions influencing the outcome space in baseline as well as mitigation scenarios**.** For regional assessments, it is also recommended to include more detailed 'real world' challenges in the scenarios that take into account factors such as limited availability of resources, limited participation of regions, suboptimal design of policy instruments and other barriers to implementation.

Acknowledgements

The research leading to these results has received funding from the European Union Seventh Framework Programme FP7/2007-2013 under grant agreement n° 282846 (LIMITS).

Chapter 3

Comparing future patterns of energy system change in 2°C scenarios with historically observed rates of change

Published article: *van Sluisveld, M.A.E., Harmsen, J.H.M., Bauer, N., McCollum, D., Riahi, K., Tavoni, M., van Vuuren, D.P., Wilson, C., van der Zwaan, B.C.C. (2015) "Comparing future patterns of energy system change in 2°C scenarios with historically observed rates of change", 35, 436-449, Global Environmental Change*

Abstract

This paper systematically compares modelled rates of change provided by global integrated assessment models aiming for the 2°C objective to historically observed rates of change. Such a comparison can provide insights into the difficulty of achieving such stringent climate stabilization scenarios. The analysis focuses specifically on the rates of change for technology expansion and diffusion, emissions and energy supply investments. The associated indicators vary in terms of system focus (technology-specific or energy system wide), temporal scale (timescale or lifetime), spatial scale (regional or global) and normalization (accounting for entire system growth or not). Although none of the indicators provide conclusive insights as to the achievability of scenarios, this study finds that indicators that look into absolute change remain within the range of historical growth frontiers for the next decade, but increase to unprecedented levels before mid-century. If overall system growth is taken into account the study finds that monetary-based normalization metrics (GDP, investments and to some degree capacity) result in less conservative outcomes than energy-based normalization metrics (primary energy). This is in particular true for indicators that experience rapid rates of change (for both technology-specify and system-focus indicators). By applying a diverse set of indicators alternative, complementary insights into how scenarios compare with historical observations are acquired but they do not provide further insights on the possibility of achieving rates of change that are beyond current day practice.

Keywords: integrated assessment modelling; energy system change; technological change; model validation; 2 degrees; feasibility

3.1 Introduction

Keeping temperature increase to less than 2°C with a high likelihood will require substantial changes in energy and land use. Integrated assessment model (IAM) studies on mitigation scenarios can provide insights into the level of the required change over time. IAM-based studies often conclude that the required transition for reaching the 2°C target is 'technically feasible', depending on the model set-up and assumptions. In the past, such studies generally considered rather idealised conditions such as full participation of all regions and sectors in climate policy. However, more recently, models have also studied the achievability of the 2°C target under less idealized circumstances assuming limits in technology availability or reduced participation in international climate policy (Clarke et al., 2009; Kriegler et al., 2014b; Riahi et al., 2015; Weyant and Kriegler, 2014). Even in those cases, most models still identify scenarios that reduce emissions in line with the 2°C target. It should, however, be noted that in their assessment, IAMs mostly account for technological and economic factors that can be easily included in the models. This, for instance, includes constraints like mitigation potentials, capital stock turnover rates, mitigation costs and inertia in investments patterns. Several other factors are not included such as the role of international negotiations, societal inertia or the time associated with decision-making processes on the one hand and behaviour changes on the other. Clearly, such factors can have a substantial influence on the probable (future) rate of change.

Historically observed rates of change can be important reference points for assessing the difficulty associated with future rates of change – providing possibly also insights in real world factors not covered in the models. In fact, several studies have already tried to compare model results and historical data using different indicators (Kramer and Haigh, 2009; Loftus et al., 2014; Riahi et al., 2015; Tavoni and van der Zwaan, 2009; van der Zwaan et al., 2013; van Vuuren et al., 2013; Wilson et al., 2012). In these studies different methods and data sets have been used to confront existing scenarios with historical evidence, meaning that their results and conclusions cannot be easily compared. For instance, van Vuuren et al. and Riahi et al. looked at overall change in emissions or emission intensity. In contrast, the studies of van der Zwaan et al. and Wilson et al. look at absolute and relative changes in the deployment of particular energy technologies. It should also be noted that model comparison projects have shown that models select different pathways in achieving similar goals, and that models can be 'diagnosed' as being more or less responsive to climate policy (Kriegler et al., 2015). In order to represent model uncertainty, it is therefore important to compare the results of a diverse set of IAMs against a standardized set of historical indicators.

In this light, the goal of this study is 1) to systematically compare several methods that use historical evidence as a basis for analyzing the difficulty associated with future energy transitions and 2) to use these methods for evaluating model results. We use the results of a multi-model study to provide insight into the uncertainty resulting from a wide diversity of technology trajectories that are consistent with the 2°C target. Questions that are addressed are:

- How do historical rates of change compare to future rates of change required under the 2°C climate objective?
- Do various indicators of technology change depict a coherent storyline?

3.2 Methodology

3.2.1 Comparing historical and future rates of change

Historical observations provide an important reference point for the required level of effort to achieve future energy system changes associated with ambitious climate policy objectives. To date, different indicators have been used to compare historical trends with future rates of change, varying in terms of system focus (technology-specific or energy system wide), temporal scale (timescale or lifetime), spatial scale (regional or global) and normalization (accounting for entire system growth). In order to gain a more holistic insight from these analyses we combine and harmonize the methods to encompass an overall similar scope of research. In the following paragraphs the various methods are described first followed by how they are interpreted in the current study. Table 3-1 and Table 3-2 provide summaries of the metrics used and scope of study. Figure 3-1 provides a visual example of the introduced methods.

3.2.1.1 Average annual capacity addition

Van der Zwaan et al. investigated historical and future capacity growth by comparing the average annual capacity additions (in GW/yr) in a multi-model context for low-carbon technologies for the short-term (2010-2030) and medium-term (2030-2050) (van der Zwaan et al., 2013). The study focused on the *absolute* rate of change required to reach the 2°C target compared to rates experienced during historical periods of rapid expansion for established technologies (e.g. natural gas power) and newer technologies (e.g., solar power). The comparison provided easy interpretable insights into the expansion rate for future deployment versus historical figures published in literature and online databases (e.g. EPIA, 2014; Platt's, 2013; US EIA, 2014).

The average capacity addition over a selected period of time (where t_0 and t_n represent respectively the starting and ending point of the timeframe under study) is defined as (see equation 1):

$$\text{Average annual capacity addition} = \frac{\sum_{t=t_0}^{t_n}\left(\text{newly installed capacity}\right)_t}{t_n - t_0} \qquad \left(\text{in } {GW}/{yr}\right) \qquad \text{(Eq. 1)}$$

Using this approach, van der Zwaan et al. concluded that future global expansion rates need to increase significantly, reaching expansion rates well beyond those observed historically in order to stay below the 2°C target. In particular the expansion of renewable energy technologies would need to be several times larger than the historical rate (van der Zwaan et al., 2013).

The comparison of *absolute* future rates with historical rates does not correct for the general growth in the size of the energy or electricity system. It is possible to account for the overall growth by normalizing the *absolute* indicators with metrics representing total system growth as presented in equation 2. The *normalization metrics* that can be used to represent total system growth are global GDP (in T$), global primary energy demand (in EJ), total electricity generation capacity (in GW) and total capital investments in the energy system (in billion USD$). For reading considerations, we predominantly use global GDP in the presented outcomes in this study, but discuss the other metrics in section 3.4.2.

Normalized average annual capacity addition =

$$\frac{\sum_{t=t_0}^{t_n}\left(\frac{\text{Newly installed capacity}}{\text{Normalization metric}}\right)_t}{t_n - t_0} \qquad \left(\text{in } \frac{{GW}/{\text{metric unit}}}{\text{year}}\right) \qquad \text{(Eq. 2)}$$

A similar analysis has been done by Loftus et al. (2014), who normalized electricity capacity deployment rates in various global decarbonization scenarios using global GDP. In their study they found that the rates of change are broadly consistent with historical experience. Only specific decarbonization scenarios with imposed restrictions on the implementation of clean and carbon sequestration technologies would lead to unprecedented rates of change for the remaining eligible low-carbon energy technologies (Loftus et al. 2014).

3.2.1.2 Technology diffusion

Technology growth dynamics are generally characterized by S-shaped curves that show an initial 'formative' phase, followed by rapid diffusion in an 'upscaling' phase and finishes into a mature 'growth' phase (Grübler et al., 1999; Wilson, 2012a). Growth rates vary over this technology lifecycle, beginning slowly until a lift-off point is reached and growth accelerates. After some time, an inflection point is passed and growth rates level off and eventually saturate, reducing growth to zero.

In this light, Wilson et al. (2012) compared historical and future dynamics of technological diffusion in the energy system by fitting logistic growth curves (with a R-squared fit of 98% or higher) to cumulative capacity time series. The advantage of using cumulative capacity over the technology's lifecycle, as opposed to installed capacity or growth rates during particular time periods, is that short-term volatility and potential selection biases towards specific periods of growth are avoided.

The (symmetrical) logistic function used in this approach is portrayed by equation 3. The parameters defining the logistic growth curve are of particular interest, as each parameter represents a specific growth characteristic used in this comparison approach. For example, the parameter defining the steepness of the curve represents the diffusion rate, whereas the parameter defining growth between 10% to 90% of saturation represents the duration of diffusion (also depicted as Δt) and the parameter describing the theoretical asymptote represents the extent of growth or saturation point of a technology (see equation 3, Figure 3-1 and Annex I). To account for the growing size of the energy system, Wilson et al. (2012) normalized the extent of diffusion by the size of the energy system (expressed in primary energy) at the midway point of each technology's lifecycle (the inflection point t_m). The normalized extent and Δt create the extent-duration relationship for the number of technologies included.

$$\text{Technology diffusion} = \frac{\left(\dfrac{\text{Extent}}{\text{Normalization metric}_{t_m}}\right)}{(1+e^{-\text{diffusion rate}*\Delta t})} \qquad \text{(Eq. 3)}$$

The main disadvantage of this methodology is that it is not readily comparable to recent observations or to maximum or frontier growth rates over short time periods. Moreover, only historical and future technologies that expose S-curve growth behaviours are included in the analysis. This excludes, for example, wind and solar power technologies which remain to have a rapid growth rate in an expanding energy system and therefore do not conform to S-curve behaviour within the time horizon of the model.

The results from the methodology applied by Wilson et al. (2012) showed that the full lifecycles of advanced power generation technologies as modelled in many future scenarios have longer durations than the full lifecycles of energy technologies that have diffused historically. In other words, there is evidence that deep decarbonization scenarios may be somewhat conservative in their long-term technology growth dynamics. However, the authors acknowledged several caveats, including the possibility that comparing long-run historical growth with long-run future growth in this way is problematic. This was specifically the case for the analysis of coal or nuclear power, which combined historical and future growth dynamics in the logistic fitting procedure.

3.2.1.3 Average annual emission decline rate

An indicator often used to gain insight into economy-wide changes is the average annual emissions decline rate (Riahi et al., 2015; van Vuuren et al., 2013). We define this indicator as given in equation 4. Similar to the annual capacity additions (described under 3.2.1.1) we consider the *average* annual decline rate over a selected period of time (where 'Emissions' describe the total CO_2 emissions and t_0 and t_n represent respectively the starting and ending point of the timeframe under study)

3

$$\text{Average annual emission decline rate} = \left(1 - \left(\frac{Emissions_{t_n}}{Emissions_{t_0}}\right)^{\frac{1}{t_n - t_0}}\right) * 100 \quad \left(\text{in } \%/_{yr}\right) \qquad \text{(Eq. 4)}$$

To account for system growth changes this study also considers the normalized version of the average annual emission decline rate (which is also known as either the intensity decline rate or decarbonization rate if GDP is considered as the normalization metric) (see equation 5).

$$\text{Normalized average annual emission decline rate} = \left(1 - \left(\frac{\left(\dfrac{Emissions_{t_n}}{\text{Normalization Metric}_{t_n}}\right)}{\left(\dfrac{Emissions_{t_0}}{\text{Normalization Metric}_{t_0}}\right)}\right)^{\frac{1}{t_n - t_0}}\right) * 100 \quad \left(\text{in } \%/_{yr}\right) \qquad \text{(Eq. 5)}$$

The disadvantage of this generic descriptive indicator is that details on underlying drivers of emissions are not visible. Moreover, as emission reduction and emission intensity decline rates have not been major policy goals in the more distant past, a comparison against the long-term historical record can be regarded as having limited relevance. Nevertheless, the study by Van Vuuren et al. (2013) used historical comparisons to conclude that emission reductions as well as decarbonization rates for scenarios consistent with the 2°C target can be regarded as extremely rapid compared to historical rates of change.

3.2.1.4 Average annual supply-side investments

Structural changes in the energy system are associated with increasing supply-side investments. As investments are also needed to achieve other social and economic goals there could be constraints in the required pace of change. Therefore, we look into the global investments into electricity generation and supply (including electricity storage and transmission and distribution, but not investments into the fossil fuel extraction sector nor the bio-energy fuel supply costs) to assess the efforts needed to mobilize an energy system transformation that is in line with the 2°C objective.

Demand-side investments are not taken into account as such estimates are subject to considerable uncertainty due to a lack of reliable statistics and definitional issues (McCollum et al. 2013). The general approach is described by equation 6 for which the *average annual supply-side investments* are calculated (where t_0 and t_n represent respectively the starting and ending point of the timeframe under study):

$$\text{Average annual supply-side investments} = \frac{\sum_{t=t_0}^{t_n} (\text{supply-side investments})_t}{t_n - t_0} \quad \left(\text{in } \$/\text{yr}\right) \qquad \text{(Eq. 6)}$$

As the total amount of investments is coupled to the size of the economy, we normalize the annual supply-side investments (see equation 7). If global GDP is considered as the

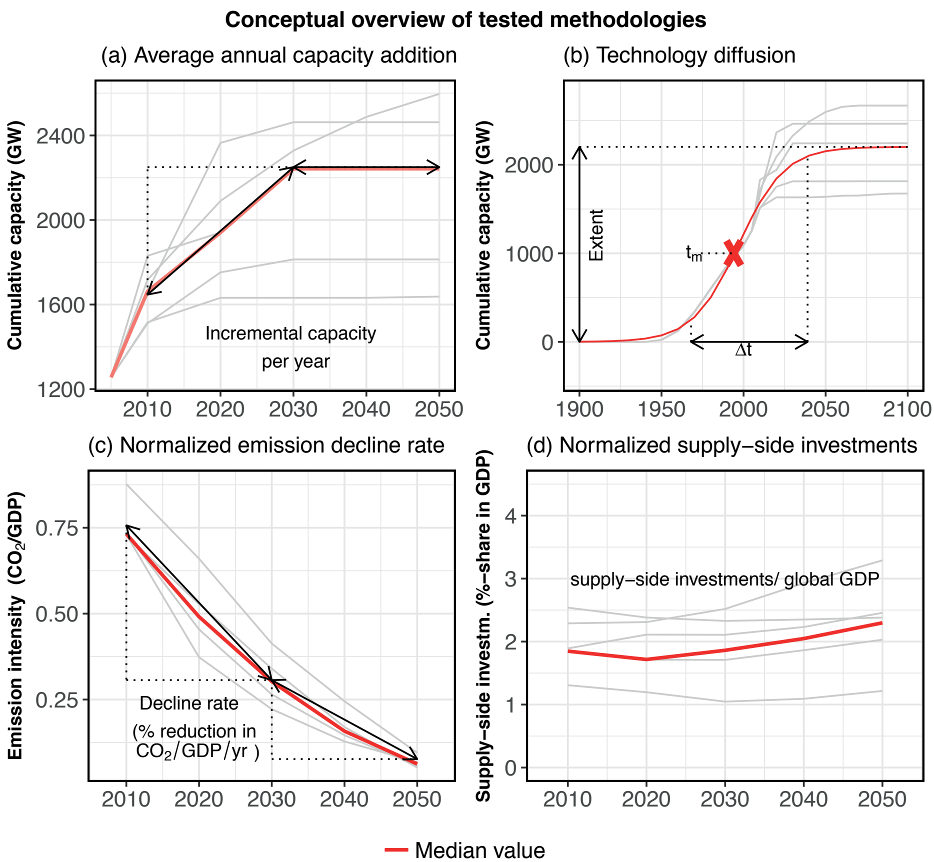


Figure 3-1 - Conceptual overview of the methodologies and key indicators. Panel (a) and (b) represent cumulative capacity of coal without CCS. Although the figure demonstrates future (modelled) trends the analysis is similar for historical trends.

Table 3-1- overview of technology change indicators included for study

Indicator	Variations	Reference	Metric
a) Average annual capacity addition	Average annual capacity addition	Equation 1	GW/yr
	Normalized average annual capacity addition	Equation 2	GW/yr/ $
b) Technology diffusion	Normalized extent and duration (Δt)	Equation 3	GW/EJ/yr
c) Average annual emission decline rates	Average annual emission decline rate	Equation 4	%/yr
	Normalized average annual emission decline rates	Equation 5	%/yr
d) Average annual supply-side investments	Average annual supply-side investments	Equation 6	$/yr
	Normalized average annual supply-side	Equation 7	%/yr

Table 3-2- overview of methodologies and the scope of this study

Indicator	System focus	Temporal scale	Spatial scale	Normalization (Metric)[2]
a) Average annual capacity addition	Technology specific	Annual[1]	Global	No
	Technology specific	Annual[1]	Global	Yes (GDP)
b) Technology diffusion	Technology specific	Lifetime	Global	Yes (Primary Energy)[3]
c) Average annual emission decline rate	Energy system	Annual[1]	Global / National	No
	Energy system	Annual[1]	Global / National	Yes (GDP)
d) Average annual supply-side investments	Energy system	Annual[1]	Global	No
	Energy system	Annual[1]	Global	Yes (GDP)

[1] On average over a selected period of time
[2] This study depicts GDP throughout the results as the measure of growth; other metrics of growth are further discussed in section 3.4.2
[3] Normalization only available for primary energy as system growth metric

normalization metric this creates an indicator reflecting investments as percentage in total GDP.

Normalized average annual supply-side investments =

$$\frac{\sum_{t=t_0}^{t_n}\left(\frac{\text{supply-side investments}}{\text{Normalization metric}}\right)_t}{t_n - t_0} \quad \left(\text{in } \frac{\$/\text{metric unit}}{\text{year}}\right) \qquad \text{(Eq. 7)}$$

McCollum et al. (2013) examined absolute rates of change for investments in more detail, concluding that future investment levels remain consistent on the short term although significant increases in investments in both developed and developing countries will be necessary over the next decades under the 2°C objective.

3.2.1.5 Future rates of change

We demonstrate the indicators by using three scenarios from a five-model study with varying assumptions on long-term international climate policy. A marked advantage of the multi-model approach is that it inherently accounts for technology biases and preferences among individual models. The study here, however, is not a model comparison: we only include the model range as an indication of the uncertainty in model results. We therefore do not discuss the results of individual models in any detail. The focus in the figures is also on the median of the range of model results.

The five global energy-environment models included in this study are: REMIND:(Bauer et al., 2013; Luderer et al., 2013); MESSAGE: (Messner and Strubegger, 1995); IMAGE: (Bouwman et al., 2006); WITCH: (Bosetti et al., 2006) and TIAM-ECN: (Keppo and Zwaan, 2011)) (see Table 3-3). These five models represent a diverse array of different solution frameworks (general equilibrium, partial equilibrium, dynamic recursive, perfect foresight and systems engineering) and differ in a variety of model characteristics, such as coverage of sectors and their disaggregation and in technological and socio-economic assumptions that determine technology diffusion.

Table 3-3 - Key model characteristics

Name	Time horizon	Model category	Intertemporal Solution Methodology
IMAGE	2100	Partial equilibrium	Recursive dynamic
MESSAGE	2100	General equilibrium	Intertemporal optimization
REMIND	2100	General equilibrium	Intertemporal optimization
TIAM-ECN	2100	Partial equilibrium	Intertemporal optimization
WITCH	2100	General equilibrium	Intertemporal optimization

The three scenarios that are used in this study are based on different policy assumptions for long-term international climate policy and have been developed as part of the LIMITS project (Kriegler et al., 2013).

(1) The baseline (*Baseline*) scenario addresses the future energy system and emission developments in the absence of climate policy. This scenario is a best reference for historical rates of change as no climate policy is involved.

(2) The second (*Reference*) scenario reflects current (unilateral) climate policy implementation based on national energy and climate targets for 2020 formulated as unconditional Copenhagen pledges. These targets are then extrapolated post-2020 by assuming similar levels of stringency in the subsequent decades. This scenario represents the current day situation and imposes no additional (technological) restrictions.

(3) The third (*2 Degrees*) scenario is a cost-optimal mitigation scenario that assumes immediate global cooperation toward the long-term target of 2°C. This scenario

represents the most optimistic view on technology availability, availability of carbon sinks and (bio-) resources to attain the 2°C climate target.

Differences are created due to the varying assumptions on long-term international climate policy, all other factors, such as the penetration and expansion rates of technologies, are treated the same across all scenarios.

The methods and indicators set out in Section 3.2.1 are comparatively applied on this set of three scenarios. As timing of change is important this study has restricted the analysis to the time period between 2010 and 2050 because it is considered most relevant for current policy and decision making.

3.2.1.6 Historical references

For the average annual capacity addition indicator, we reconstruct a similar analysis to that of van der Zwaan et al. (2013) by comparing modelled average annual rates of change in total new installed capacity to historical average annual rates of change. Several databases provided historical data on various technologies (see Table 3-4) of which the decade with the largest absolute growth in capacity is selected for further analysis.

Table 3-4 - Overview of selected historical timeframes per indicator and the used databases

Indicator	Technology	Historical reference	Source
a) Average annual capacity addition	PV	2003-2013	EPIA (2014
	Wind	2003-2013	GWEC (2014)
	Nuclear	1980-1990	Platts (2013)
	Biomass	2005-2011	US EIA (2014)
	Fossil	2003-2012	Platts (2013)
	CCS	-	-
b) Technology diffusion	PV	1970s	Wilson et al. (2012)
	Wind	1970s	
	Nuclear	1950s	
	Fossil	Early 1900s	
c) Average annual emission decline rate	System	1970s-2000	Riahi et al. (2015)
d) Average annual supply-side investments	System	2000-2013	IEA (2014a)

For the technology diffusion indicator, similar logistic growth curves are constructed as in Wilson et al. (2012) on both historical (if applicable) and future time series. The historical time series begin as far back as the early 1900s (natural gas and coal power), the 1950s (nuclear power), the 1970s (wind power and solar PV), or start no sooner than the 2020s or later (CCS – thus fully based on modelled data only).

For the average annual emission decline rate indicator, we depict average CO_2 emission and CO_2 intensity reduction rates and compare them to historical national events that led to emission (intensity) reductions (such as oil crises, collapse of political regime) (Riahi et al., 2015; Van Vuuren et al., 2013).

For the average annual supply-side investments indicator, we show the average annual investments or the share in GDP over the 2010–2050 timeframe and compare them to the historical investments (or share in GDP) over the 2000-2013 timeframe (IEA, 2014a).

In order to normalize the *absolute* indicators to take into account relative changes in the size of the energy system or economy, we use GDP, primary energy, total energy system investments and total capacity as normalization metrics. The historical period taken into consideration is the 1980-2012 period as most metrics have annual data available in public sources with investments as an exception (see Table 3-5). The analysis will predominantly focus on global GDP as the main system growth factor; other metrics will be discussed in section 3.4.2.

Table 3-5 - Overview of normalization metrics, available historical timeframe and source

Method	Metric	(Historical) timeframe	Source
Normalization	GDP	1980-2012	The World Bank (2015)
	Primary Energy	1980-2012	US EIA (2014)
	Investments	2000-2013	IEA (2014a)
	Capacity|Electricity	1980-2012	US EIA (2014)

3.3 Results

In the results below, we show the results of each of the indicators presented in Section 3.2 for the three LIMITS scenarios and all 5 models as well as the historical reference period.

3.3.1 Average annual capacity addition

The modelled annual capacity additions (in GW) for the 2010-2030 period are on average consistent with the historical reference across all three scenarios. In the *Baseline* scenario, the expansion rates from 2010-2030 are broadly consistent with historical observations (see Figure 3-2). Coal without CCS maintains a constant annual expansion rate whereas gas without CCS will nearly double its current annual expansion rate, matching and overtaking coal without CCS. Under climate constraints, we find a shift away from fossil fuels either shifting to a less carbon-intense substitute (gas) or shifting to non-fossil resources. For solar PV, wind and biomass the expansion rates stay within historical peak observations. The projections of nuclear power capacity growth are also consistent with historically observed expansion rates. However, currently planned additional nuclear capacity between 2015-2019 (World Nuclear Association, 2014) indicates that the expansion rate of nuclear energy will most likely not exceed the 3GW/yr. Hence, given the long inertia in nuclear power plant planning and construction process, the

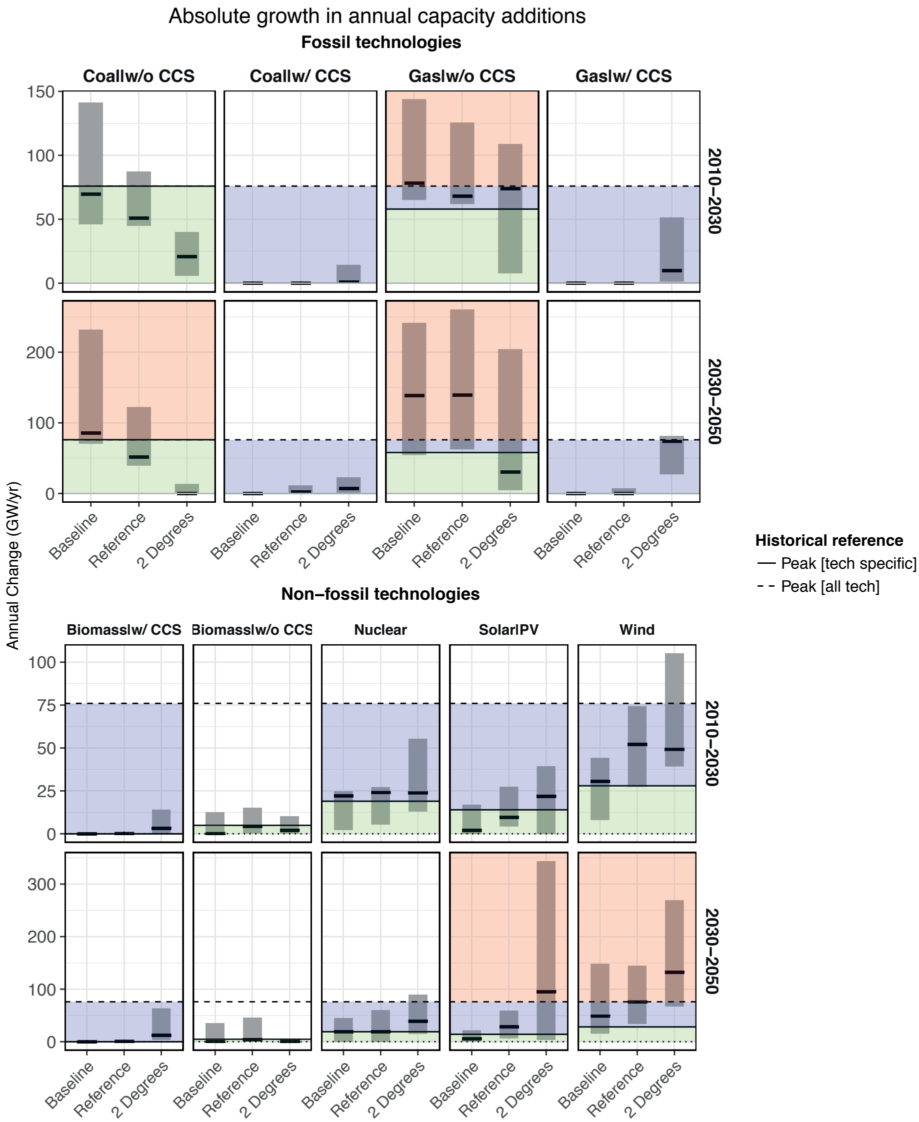


Figure 3-2 - Average annual capacity additions (over the 2010-2030 and 2030-2050 period) for various electricity-generation technologies under different climate policy assumptions. The horizontal lines indicate the technology-specific peak or maximum value observed historically (solid lines) and the peak value across all technologies which is given by coal without CCS (dotted lines). The green, blue and red areas indicate whether a historical benchmark has been exceeded (red for all-technology peak, blue for technology-specific peak) or not (green). The bars indicate the range of modelled rates of change with the median value highlighted in black inside the bars.

actual expansion rates of nuclear power might continue to be below the deployment rates as depicted in some of the high scenarios.

In the 2030-2050 timeframe, the modelled rates of annual capacity additions increase beyond technology-specific expansion rates observed historically. Some even venture

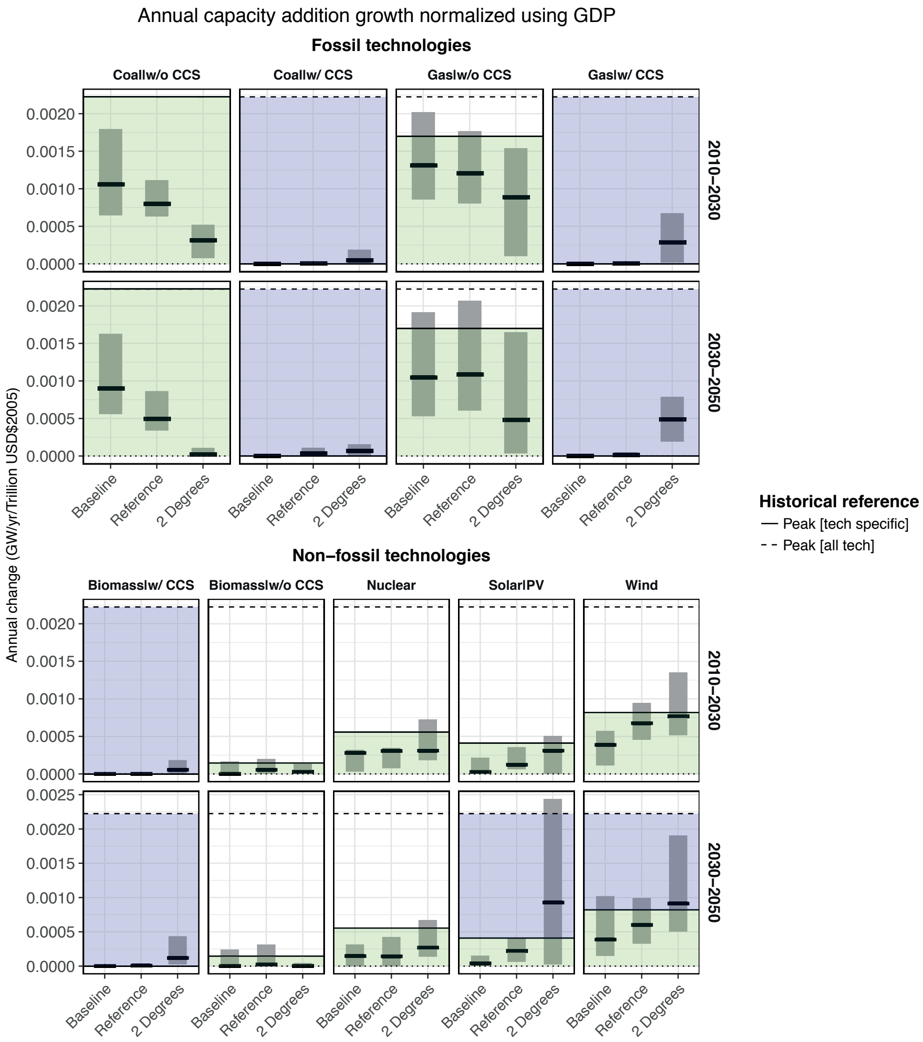


Figure 3-3 -Average annual capacity additions (GW/yr), normalized using GDP (in trillion US$2005) for both historical data as well as scenario projections. The horizontal lines indicate the technology specific maximum value and the maximum value of any technology in the past. The green, blue and red areas indicate whether a historical benchmark has been exceeded (green below technology specific rate; blue above technology specific rate; red above the historical rate of any technology). The bars indicate the range of modelled rates of change with the median value highlighted in black inside the bars

into territory that goes beyond overall best system achievement from the past. Under *Baseline* assumptions, this is the case for both coal and gas without CCS, which will expand their growth to unprecedented levels as fossil fuels remain the fuel of choice. Under the 2°C objective (*2 Degrees*), it will be the growth of solar and wind capacity that becomes particularly rapid, showing deployment rates above the historical peak value of overall system achievements.

The outcomes change if overall system growth between historical and modelled periods is taken into account (by normalizing the average annual capacity indicator using global GDP growth). On the short-term the modelled average annual capacity additions show to remain consistent with technology-specific expansion rates of the past (see Figure 3-3). However, although some technologies (wind and solar in particular) will exceed their technology-specific historical reference on the mid-term, all remain in line with the overall best system achievement from the past.

3.3.2 Technology diffusion

If the extent-duration relationships for all electricity generation technologies and scenarios are assessed (see Figure 3-4) we find that all technologies follow the historically observed patterns. However, under *Baseline* assumptions the diffusion durations (Δt) are generally longer (further to the right) and an eventual saturation point (extent) is reached beyond the time horizon of the models involved (presented as a duration that is bigger than a 100 years in Figure 3-4).

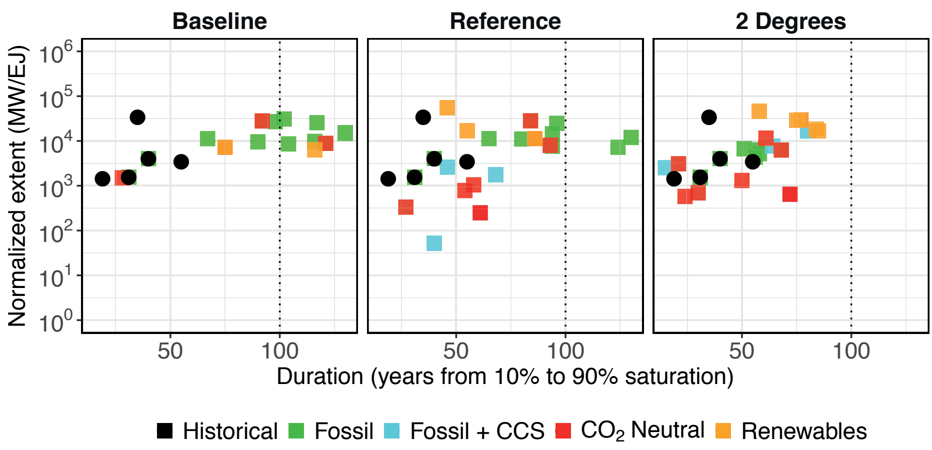


Figure 3-4 - Capacity growth of energy technologies in 3 future scenarios of the 21st century: extent vs. duration of growth using fitted logistic function parameters. Black dots represent historical extent-duration relationships of various energy-supply technologies (such as nuclear, coal and gas without CCS, hydro and refineries (FCC)).

Once climate policies are introduced (e.g. the *Reference* and *2 Degrees* scenarios), the extent-duration relationships change. All technologies show to shift to the left (shorter diffusion durations). For fossil without CCS technologies this implies a lower capacity saturation level, a shorter lifecycle, and some capacity reduction in the year in which maximum growth is achieved (see also Annex I). For clean technologies (fossil with CCS, CO_2 neutral and renewable energy technologies) on the other hand, greater extents of growth are achieved with shorter diffusion durations. However, despite the shorter diffusion duration, the rates remain above the historically observed reference. In that sense this study is in agreement with Wilson et al. (2012) concluding that the modelled diffusion rates appear to be conservative compared to historically successful technologies.

3.3.3 Average annual emission decline rate

Figure 3-5 shows the average annual emission decline rate and the decline rate normalized using GDP (creating a carbon intensity decline rate or decarbonization rate). Up till today, only rare historical occurrences on a national level have led to significantly higher reduction rates than the global average, which have been negative (-0,8% per year on average throughout the 1970-2010 period) owing to continuously growing emissions worldwide. For example, fairly swift emission reduction rates were observed in Sweden from 1974 to 2000 as a result of policy impulses on greening the Swedish energy system after the oil crisis in 1973 (2-3% per year). Another example is the emission decline rate of 2-4% per year for Eastern European and former Soviet Union countries after the collapse of the Soviet Union (Riahi et al., 2015). To stay in line with the 2°C objective a sustained global carbon emission reduction rate of about 1% till 2030 is required, remaining within the earlier discussed regional historical boundaries. However, after 2030 the models depict a sustained global carbon emission reduction rate of 5% which goes beyond both global and regional historical achievements.

Similarly, the global decarbonization rate (average annual emission decline rate normalized with GDP) has been around 0.5% over the period 1900–2010 and around 1% over the 1970–2010 (driven by technological change and sectoral shifts) (Van Vuuren et al., 2013). If compared to the modelled decarbonization rates, we find ranges of 2-3% under *Reference* scenario assumptions whereas the margins expand to 6-10% by 2050 if 2°C is to be attained at the end of the century. These rates are considerably higher than the global average rate experienced in the past. At the regional level, historically faster rates can be observed than the global average: some Asian regions have managed to achieve decarbonization rates of 3-5% per year during the late 1980s and early 1990s. This would imply that the global rate would need to increase significantly, but also go beyond the most rapid (local) decarbonization rate experienced in the recent past and maintain this rate (globally) for several decades.

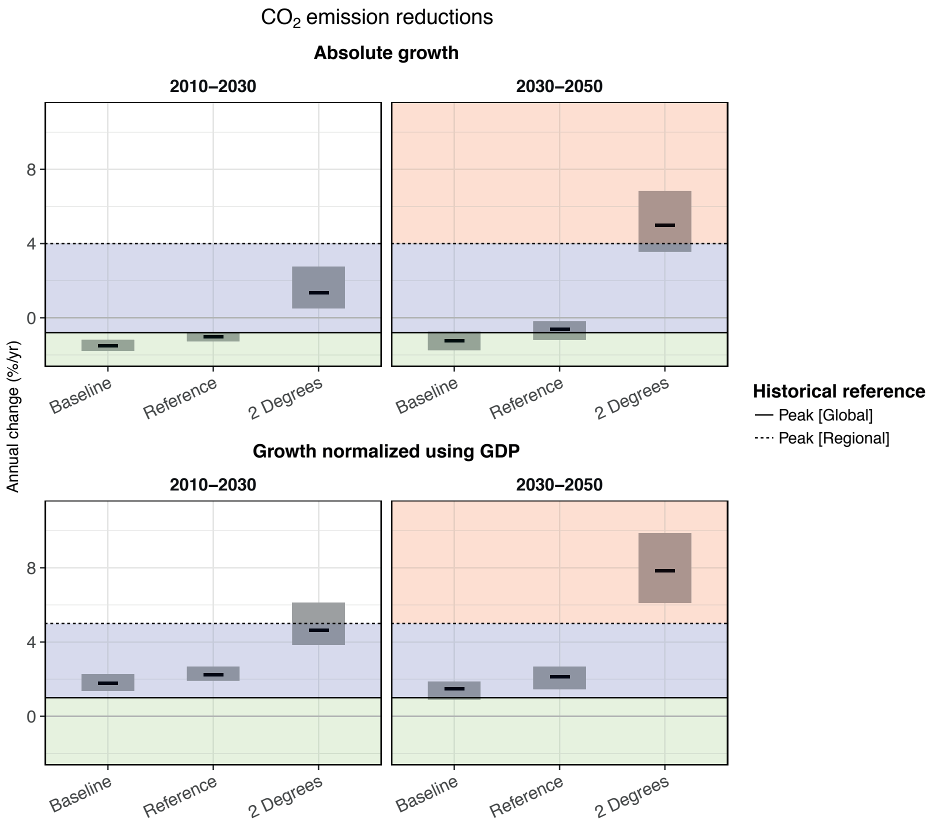


Figure 3-5 – Average annual emissions decline rates (top) and normalized average annual emission decline rates (bottom). Negative numbers indicate emissions increase. Green area implies consistency with historical evidence for global rates, blue represents values within historical bounds of the fastest regional reduction addressed and red implies beyond historical reference for either considered spatial scale. The bars indicate the range of modelled rates of change with the median value highlighted in black inside the bars.

3.3.4 *Average annual supply-side investments*

Rapid transitions in the energy system are associated with increasing investment flows compared to the status-quo, which is reflected in Figure 3-6. Both current climate policy (*Reference*) as well as the 2°C pathway (*2 Degrees)* would require greater investments than the business-as-usual case (*Baseline*), climbing up on the short term to about 1.5 trillion USD per year which is slightly greater than observed historically. Under 2°C ambitions these investment levels are modelled to nearly double for the subsequent decade, increasing up to 2.5 trillion USD per year on average. Upscaling investments to these levels might pose several difficulties as two-third of the total sum is levied by developing areas (McCollum et al., 2013) which require finance mechanisms other than their own domestic funds (Bowen et al., 2014).

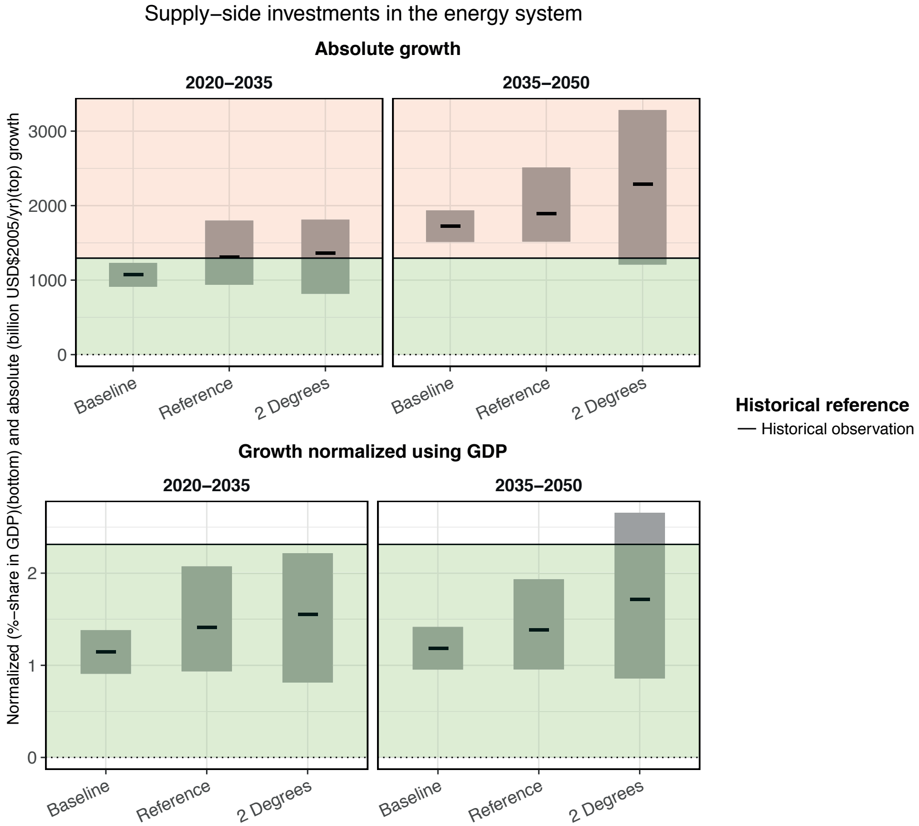


Figure 3-6 – Average annual supply-side investments (top) and average annual supply-side investments in GDP (bottom). Bars represent the range of model outcomes of respectively *Baseline*, *Reference* and *2 Degrees*[1]. The bars indicate the range of modelled rates of change with the median value highlighted in black inside the bars.

1 For the *Baseline* scenario, the numbers are recalculated, as they were not included in the study of McCollum et al. (2013). Due to data availability, only results for IMAGE and MESSAGE are shown here. The *2 Degrees* scenario includes unilateral climate policy targets till 2020, suspending immediate global action, and therefore deviating from the *2 Degrees* scenario as presented in other graphs. As the *Reference* and *2 Degrees* scenario start to deviate only after 2020 the time periods are amended to 2020-2035 and 2035-2050. The historical observation consists of cumulative energy supply investments and cumulative total GDP from 2000-2013.

If total supply-side investments are expressed as a share in global GDP, it shows that the ratio remains within the bounds of historical experience. However, by looking into global rates it potentially masks the large differences between regions. The average investment intensity of developing economies was around 3.5%, whereas it was just 1.3% in industrialized countries (McColumn et al., 2014).

3.4 Discussion

3.4.1 Comparative overview of indicators and results

This study uses a diverse set of indicators that assess the consistency of modelled future energy transitions with the historical record. The study yields ambiguous insights into the consistency of modelled rates of change with historical observations (see Table 3-6). Absolute and near-term (2010-2030) rates of change vary in their consistency with historical observations for the three scenarios, although these are mostly within the range of overall system achievements (blue shaded areas on the graphs). By normalizing the indicators to account for system growth it shows an overall consistency with historical records. Over the longer term the indicators create a near similar picture for the *Baseline* and *Reference* scenarios. However various significant differences emerge

Table 3-6 - Summary of comparisons between historical observations and three modelled scenarios using a diverse set of indicators. For plotting convenience the fossil and renewable technologies are grouped - the table considers the highest rate of change in the group per scenario

			Absolute growth			**Normalized growth**		
			Baseline	Reference	2 Degrees	Baseline	Reference	2 Degrees
2010-2030	Average annual capacity additions	Fossil						
		Non-Fossil						
	Average annual emission decline rates	System						
	Average annual supply-side investments	System						
2030-2050	Average annual capacity additions	Fossil						
		Non-Fossil						
	Average annual emission decline rates	System						
	Average annual supply-side investments	System						
	Technology diffusion	Tech-specific						

- Not applicable
- Below historical growth frontier for corresponding technology
- Below historical growth frontier for any technology
- Above historical growth frontier for any technology

under the 2-degree objective (*2 Degrees*), specifically in terms of (absolute) average annual capacity expansion rates, (absolute) average annual energy-supply investments and (absolute and normalized) average annual emission decline rates.

3.4.2 Methodological diversity and issues

The indicators used vary in focus and scope. In this section we further discuss the influences and sensitivities of the study design on the outcome.

(1) **System focus:** Models are inherently limited in their representation of energy-economy dynamics, and are highly dependent on their technological resolution (number of technologies included), underlying assumptions (on e.g. capital replacement or learning rates) as well as model structure and solution frameworks. In that respect technology-specific indicators are potentially more sensitive to specific model behaviour than system-wide indicators. However, in a multi-model set-up these sensitivities are more-or-less balanced out and in that case, as depicted in Table 3-6, system indicators are not consistently more or less likely to remain consistent with historical observations than technology-specific ones;

(2) **Temporal scale:** Indicators that focus on a specific timeframe (e.g. the average annual capacity additions or average annual emission decline rates) can be sensitive to the selected time period under study. This is especially the case if rapid expansion or declines rates are nested in certain periods of time, which can be either highlighted or numbed down in the longer-term average.

    Focusing on the full technology lifecycle, however, can also influence the results. For example, the Wilson et al (2012) methodology is sensitive to technology projections with a clear logistic growth profile, such as mature historical technologies for which long time-series data are available. As renewable technologies are generally still in their early deployment phase these are not expected to saturate in the timeframe of the model, and will therefore not appear as logistic growth profiles in the Wilson et al. methodology. Hence, some modelled rates of change will not find application in the extent-duration analyses. The conservatism in the extent-duration curves could thus be an outcome of the overrepresentation of incumbent technologies;

(3) **Spatial scale:** By focusing on global outcomes an indicator may potentially mask the large differences between regions. In this light the indicator provides only limited insights into the actual challenges that are faced to reach such rates of change. In the case where a global benchmark is absent (such is the case for (normalized) emission decline rates) we selected a more local (contemporary) achieved peak value. Such

a comparison inherently includes selection bias as frontier reduction rates have specifically been selected. However, although these regional benchmarks only lasted for a short period of time and emerged under rare circumstances (such as oil crises and regime changes), these specifically underline the difficulty of achieving the needed rates of change;

(4) **Normalization:** The normalization approach is visibly sensitive to the type of system growth metric used (see Figure 3-7). Monetary-based normalization metrics (GDP, investments and capacity to some degree as well) result in more conservative rates of change than energy-based normalization metrics (primary energy). As a result, rates of change that are normalized by using monetary-based normalization metrics are less likely to exceed historical rates than those normalized using energy-based metrics. This is in particular true for indicators that experience rapid rates of change (for both technology-specify and system-focus indicators).

Choosing the appropriate normalization metric is important – as the choice for a specific metric could render future rates of change (in)consistent with historical rates. The choice depends according to the authors on (a) the variable being normalized, and (b) the question being asked. For example, if the modelled variable is annual capacity additions, then (a) suggests using historical primary energy or capacity as the normalization metric, unless (b) the specific question is whether investment requirements in new capacity are in line with historical observations.

In sum, the results of the indicators discussed in this study are associated with several methodological considerations. Applying a wide set of indicators therefore offers alternative, complementary insights into how scenarios compare with historical observations on two different scales (e.g. technology-specific and system-wide indicators and the choice for normalization). Although none of the indicators provide conclusive insights as to the achievability of scenarios they are useful ways to contribute to scenario evaluation and provoke critical interpretation of results.

3.4.3 Expanding the scope of research

By applying a diverse set of indicators one can gain more holistic insights into how scenarios compare with historical observations. Further research in line with this study could focus on:

(1) **Fine-tuning and extending the scope of current indicators:** Two fundamental regularities of successful technology diffusion patterns are described in Kramer and Haigh (2009). According to their study, the build rate of new and existing energy

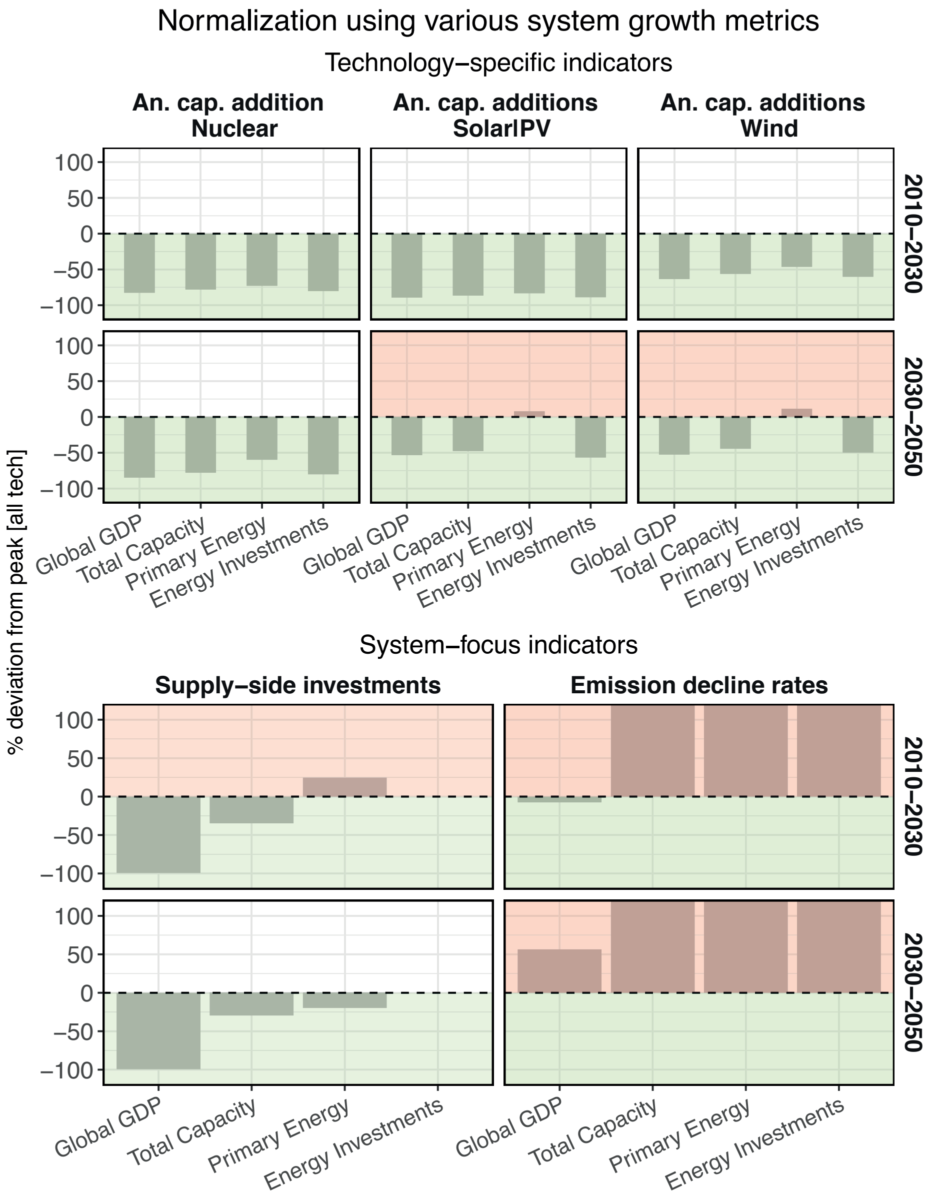


Figure 3-7 - Deviation of the median model value from the maximum peak benchmark per indicator for each considered normalization metric. Positive values indicate that the indicator exceeded historical experience whereas negative values imply consistency with historical observations. For plotting convenience the annual capacity additions are limited to nuclear, solar PV and wind technologies. Moreover, the investments indicator is plotted on the 2010-2030 and 2030-2050 timeframe but these represent the timeframes as depicted in paragraph 3.3.4. The picture focuses on the 2°C objective.

technologies follow two 'laws' which have been fairly consistent across energy technologies in the past. The first law describes how technologies grow quickly for the first two decades at exponential rates (+/-26%/yr) until 'materiality' is reached, defined as a +/-1% share of the global energy system. The second law states that after materiality, growth rates level down to an eventual equilibrium or constant market share. Although the expansion phase and the maturing growth phase characterized by Wilson et al. (2012) broadly correspond with these 'fundamental laws', this could be embedded more clearly within the historical comparison methods. Moreover, additional insights may also be acquired by distinguishing between expanding systems (adding new capacity) and stabilizing systems (substituting existing capacity);

(2) **Introducing additional comparison methods:** Modelled rates of change could be compared against actual trends over the same period of time, for instance a decade after the original projection was made. An example of such an exercise is found in van Vuuren and O'Neill (2006). If short-term model trajectories are significantly inconsistent with historical trajectories, it could expose conservatism in the long-term scenario logic and the assumptions on the driving forces. This methodology is, however, only useful if historical trends include similar climate policies as included in the model projections;

(3) **Including demand-side indicators:** Historical and future emissions and their driving forces have also previously been studied by applying the Kaya-identity (Kaya, 1990). The Kaya-decomposition analysis is applied in numerous studies (i.e. Steckel et al., 2011; Zhang et al., 2009) to examine the implications of changes in total CO_2 emissions on affluence (representing growth of economic activities), change in energy intensity (i.e. total primary energy over GPD reflecting efficiency and consumption patterns) and the carbon intensity (i.e. total CO_2 emissions over total primary energy). The three components could be assessed in tandem or as separate indicators in comparative work of prospective studies and historical records. This study has a greater energy supply orientation as all indicators focus on either energy supply technologies, investments or the carbon intensity of energy supply but future work could also include demand side indicators such as energy intensity and affluence;

(4) **Going beyond the historical benchmark:** This study considers history as an important benchmark, though history provides only limited information when looking at innovation. For example the results provide no further information about, amongst others, the drivers of technological change, (perceived) risks, scalability,

structure of the industry or role of institutions. Expert elicitation could expand the knowledge on critical implementation barriers and further test the feasibility of prospective studies. Several prospective studies on technology development use expert elicitation protocols as a research tool to assess the feasibility of emerging (carbon-free) energy technologies (see for example Bosetti et al. 2012, Jenni et al. 2013, Fiorese et al. 2014). Experts can go beyond the historical benchmark by providing, for example, probabilistic information on the likelihood that technologies will overcome particular hurdles and estimate the overall probability of success for each technology (Baker et al., 2009a).

3.5 Conclusions

In this study we have compared indicators of change in future scenarios to historical trends for various degrees of climate policy. The analysis confronts scenario data from the LIMITS project to four methodologies that focus on different indicators of technology change, such as the average annual capacity additions, technology diffusion and changes in emission trends or investments. The main conclusions of this analysis are:

The achievability of future rates of change depends on the indicator used. In this study, we assessed a variety of indicators to look at the rate of future change versus historically achieved rates of change. This comparison provides some insight into the effort involved in achieving these scenarios but is highly dependent on: (1) the selected historical benchmark, (2) normalization, (3) data availability as well as the (4) underlying economic and technological assumptions, model structures and the included level of technological detail in the models. Although none of the indicators provide conclusive insights on the achievability of scenarios they are useful ways to contribute to scenario evaluation and provoke critical interpretation of results.

Indicators highlight that absolute rates of change in scenarios achieving the 2 degree target are rapid in the medium term compared to historically achieved rates of change. In absolute terms we have observed that projections are more-or-less in line with reported achievements on the short-term, but these increase to unprecedented levels by mid-century. Specifically the average annual capacity addition rates for solar and wind and the required energy-supply investments are particularly strong under 2°C constraints, showing rates above the historical peak value of overall system achievements by 2030.

Methods that look at relative rates of change by comparing the change to overall growth in the system conclude that future rates of change are generally within the range of successful transitions in the past. Indicators that account for the growth in the overall system show that the modelled rates of change in the scenarios are lower compared to the rates of change in the past. We find that monetary-based normalization metrics (GDP, investments and to some degree capacity) result in less conservative normalization than energy-based normalization metrics (primary energy). This is in particular true for indicators that experience rapid rates of change (for both technology-specific and system-focus indicators)

Acknowledgements

The research leading to these results has received funding from the European Union Seventh Framework Programme FP7/2007-2013 under grant agreement n° 282846 (LIMITS) and n° 603942 (PATHWAYS). The authors are indebted to Peter Kolp at the International Institute for Applied Systems Analysis (IIASA) for providing invaluable technical support.

Annex I: overview table of capacity saturation, duration, and max growth speed

Table A1-1 - overview table of capacity saturation, duration, and max growth speed. Calculated from the LIMITS scenarios using the methodology of Wilson et al. (2012). Ranges given are a result of the 5 global integrated assessment models used in this analysis.

		Extent (GW)		Δt(yrs)		Tm	
Scenario	**Variable**	**min**	**max**	**min**	**max**	**min**	**max**
Baseline	Biomass|w/o CCS	845	845	84	84	2051	2051
Baseline	Coal|w/o CCS	7748	31320	102	130	2044	2086
Baseline	Gas|w/o CCS	8059	32889	67	116	2041	2084
Baseline	Nuclear	471	9407	28	127	1985	2092
Baseline	Wind	6978	9088	75	116	2082	2087
Reference	Biomass|w/ CCS	300	1042	54	61	2080	2092
Reference	Biomass|w/o CCS	3430	3430	61	61	2058	2058
Reference	Coal|w/ CCS	68	2586	40	68	2077	2094
Reference	Coal|w/o CCS	4523	10308	80	130	2023	2060
Reference	Gas|w/ CCS	359	359	27	27	2074	2074
Reference	Gas|w/o CCS	9536	28756	65	96	2040	2076
Reference	Nuclear	2636	10664	98	130	2051	2085
Reference	Solar	16125	72242	46	55	2074	2093
Reference	Wind	12738	12738	86	86	2081	2081
2 Degrees	Biomass|w/ CCS	351	5551	24	72	2038	2074
2 Degrees	Biomass|w/o CCS	385	385	91	91	2056	2056
2 Degrees	Coal|w/ CCS	451	451	30	30	2046	2046
2 Degrees	Coal|w/o CCS	1840	2704	57	68	1992	2003
2 Degrees	Gas|w/ CCS	1400	7721	15	80	2028	2075
2 Degrees	Gas|w/o CCS	2254	3529	51	56	2015	2019
2 Degrees	Nuclear	4119	11600	101	149	2073	2080
2 Degrees	Solar	14096	39538	58	75	2077	2087
2 Degrees	Wind	7849	23829	77	85	2068	2080

Chapter 4

Comparing future patterns of energy system change in 2°C scenarios to expert projections

Submitted, in review: *van Sluisveld, M.A.E., Harmsen, J.H.M., van Vuuren, D.P., Bosetti, V., Wilson, C., van der Zwaan, B.C.C. (submitted) "Comparing future patterns of energy system change in 2°C scenarios to expert projections"*

Abstract

Integrated assessment models (IAMs) are widely used to assess the implications of human activity on climate change and to explore possible response strategies. IAMs have, however, also been critiqued for their (necessarily) simplified simulation of real-world processes. The aim of this paper is to assess whether IAM projections diverge in systematic ways from expert projections as a result of their configuration. We carried out an expert elicitation on technology deployment for business-as-usual and stringent climate policy scenarios and for the near (2030) and medium (2050) term. We compared the outcomes of the expert elicitation to IAM projections on solar, wind, biomass, nuclear and carbon capture and storage (CCS) deployment to identify systematic differences as well as commonalities between these two sources of insight on future energy system change. A relatively high agreement between IAMs and experts was found on system developments for a business-as-usual scenario. Some disagreement between IAMs and experts was found under stringent climate policy assumptions. Compared to experts, IAMs project overall greater use of CCS, nuclear power and the combination of bio-energy and CCS. These are generally large unit-scale technologies, deployed in centralised power systems. In contrast, experts projected stronger growth in renewable energy technologies, and particularly for solar power. The systematic differences in perspective on future systems change between experts and IAMs are argued to be a result of differences in system representation, the periods in which projections were collected and compared and assumptions on future change under 2°C considerations.

Keywords: Technology diffusion, integrated assessment, climate change, 2 degrees, expert elicitation

4.1 Introduction

Integrated assessment models (IAMs) are analytical tools used to assess the implications of human activity on the climate system and to explore possible response strategies to climate change. Scenarios generated by these models provide analytical guidance on strategic policy planning elements such as the timing of greenhouse gas (GHG) emission reductions, the required changes in the technological infrastructure, and the potential contribution of different world regions to limiting global temperature increase (e.g. Calvin et al. (2012); Kriegler et al. (2013); Riahi et al. (2015); Tavoni et al. (2015); Weyant and Kriegler (2014)). Model-based scenarios play an important role in informing society about the effects of future policies. For example, the assessment of long-term global system change by the Intergovernmental Panel on Climate Change (IPCC) has relied heavily on a database of about 1200 model-based scenarios (Clarke et al., 2014). Subsequently, the assessment reports by the IPCC have been helpful in informing negotiators and heads of state in articulating long-term ambitions. For example, the IPCC's *fourth Assessment Report* (AR4) has provided the underpinning of the European Unions' ambitions to reduce GHG emissions by 80%-95% in 2050 compared to 1990 levels (Council of the European Union, 2009; Gupta et al., 2007), while the IPCC's *fifth Assessment Report* (AR5) has provided the underpinning of the communicated ambitions by the G7 during the Paris Agreement (stating to reduce global GHG emissions by 40%-70% in 2050 compared to 2010 levels) (G7, 2015; UN, 2015). Due to this rising importance of model-based scenarios in climate change mitigation planning, interest has sharpened on the evaluation of IAMs and their depictions of achievable technological growth under stringent climate mitigation assumptions (Anderson, 2015; Anderson and Peters, 2016; Fuss et al., 2014).

Literature evaluating the ability of IAMs (and related models) to adequately capture future energy system change has emphasised the difficulty of using formal model validation methods (Schwanitz, 2013). One reason is that IAMs are designed to capture long-run dynamics of aggregated human (techno-economic) activity and *not* short-term and more volatile processes. This means that comparing IAM projections to recent observations has limited relevance for model evaluation. However, in order to evaluate the patterns of future development in IAMs, one can use methods such as (1) inter-model comparison, to seek the dominant pattern within multiple IAM-models (Kriegler et al., 2015; Riahi et al., 2015; Tavoni et al., 2015), (2) comparative analysis with long-run observational datasets, to gain insight on whether depicted trends on the speed of technological diffusion and scalability of technologies are within historical evidence (Kramer and Haigh, 2009; van der Zwaan et al., 2013; van Sluisveld et al., 2015; Wilson et al., 2012) and (3) retrospective analysis, to test whether modelled system behaviour has approached the development of its real-world analogue in the past (Fujimori et al., 2016;

Metayer et al., 2015; Trutnevyte et al., 2016; van Vuuren and O'Neill, 2006). While such studies provide insight into the performance of IAMs in representing (future) system change, these methods remain focussed on past insights and materialised change and take little note of current day innovation processes and development. As a result, IAM studies may include systemic inertia in their projections on future change.

Several strands of literature have applied alternative methods to acquire insights on future development. One of those alternative methods is to systematically consult specialists of a specific field of expertise. Experts have the ability to interpret the wealth of (tacit) information on current societal movements and consider their implications for the future. Collecting this knowledge, by means of an expert elicitation, has the advantage of testing hypotheses and gauging the uncertainties that move beyond the status-quo (Bosetti et al., 2016). For example, various expert elicitations have focussed on the change of costs for electricity under various descriptive scenarios on RD&D funding. Examples include elicitations on biomass energy (Fiorese et al., 2014), solar PV (Bosetti et al., 2012; Curtright et al., 2008), nuclear energy (Anadón et al., 2012; Baker et al., 2008) and carbon capture and storage (CCS) (Baker et al., 2009b; Chan et al., 2011; Nemet et al., 2013; Rao et al., 2006) technologies. Although such consultations provide useful reference points for future projections, expert judgements are known to be susceptible to cognitive biases (Marquard and Robinson, 2008) and usually do not stretch over very long time scales. In that light, expert elicitations may only provide limited guidance to meeting long-term climate objectives.

In the context of the debate on the technological growth depictions in IAMs, this study presents a comparative analysis of two different analytical methods that are both used to assess future change. This study focuses particularly on the quantitative projections provided by IAMs and the quantitative estimates by experts that are acquired through expert elicitation. We use the IAM results and the outcomes of the expert elicitation to highlight similarities and differences on future technological deployment levels, but also to identify the strengths and weaknesses of both methods to assess future system change. To our knowledge, expert elicitations have rarely focused on the deployment levels of technologies, nor have they been directly compared to IAM outcomes. The few expert elicitation studies that have looked into the growth and diffusion of energy technologies have predominantly focused on the driving forces and evaluation criteria (see e.g. Napp et al. (2015); Vaughan and Gough (2016)). This type of research has thus mostly remained on a qualitative level which cannot directly be compared to IAM output. To conduct the study, we address the following research questions:

- Do expert judgements deviate from model projections of future rates of technological change in the near-term (2030) to medium-term (2050)?

- What are the reasons for any differences observed between IAM and expert projections?

As the decarbonisation of the power sector can be considered as the most prominent response strategy to meeting long-term climate targets in IAMs, we focus on the key electricity-supply technologies that contribute to decarbonisation (respectively solar PV, wind, nuclear, biomass and thermal plants combined with and without carbon removal technologies (CCS)).

4.2 Methodology

4.2.1 Models and scenarios

Integrated assessment models are analytical instruments used to explore different futures or to look into the changes required to meet a predetermined policy objective. IAMs typically represent relevant interactions and feedbacks within the human and earth system, with a particular focus on the energy system, land system and climate system. Two distinct IAMs can be recognised in literature (Edmonds et al., 2012), which are the highly aggregated IAMs used for cost-benefit analysis (considered to be relatively simple and stylised models) and the high resolution IAMs used to assess the climatic response of specific human activities (demand for services, use of energy). The results of the latter type are most commonly reported in assessments on human activities and their impacts to the global system (Clarke et al., 2014).

4.2.1.1 Selection of Integrated Assessment Models

In this study we focus on an ensemble of high resolution IAMs that have a history in reporting on systemic change over long temporal scales and with different climate objectives (respectively AIM-Enduse (Kainuma et al., 2004); GCAM (Clarke et al., 2007); IMAGE (Stehfest et al., 2014); MESSAGE (Messner and Strubegger, 1995); REMIND (Bauer et al., 2013; Luderer et al., 2013); WITCH (Bosetti et al., 2006) and TIAM-ECN (Keppo and Zwaan, 2011)). These models vary in terms of (1) their coverage of the economy (e.g. general equilibrium models contain detailed macro-economic representation, whereas partial equilibrium models describe markets and processes in more detail while treating the economy exogenously) and (2) their degree of foresight (with no foresight leading to system balancing with each new time step [recursive dynamic] and some foresight allowing for optimisation) (Kriegler et al., 2015). As such, these seven models represent a diverse set of solution frameworks and model characteristics (see Table 4-1), varying in terms of their spatial, sectoral and technological resolution (high or low technological diversity), as well as in their assumptions that drive technology diffusion (high, medium or low response).

Table 4-1 - Key model characteristics, adapted from (Kriegler et al., 2015)

Name	Time horizon	Model category	Intertemporal Solution Methodology	Tech diversity in low carbon supply	Classification*1
AIM-Enduse	2050	Partial equilibrium	Recursive dynamic	High	Medium response
GCAM	2100	Partial equilibrium	Recursive dynamic	High	High response
IMAGE	2100	Partial equilibrium	Recursive dynamic	High	High response
MESSAGE	2100	Partial equilibrium	Intertemporal optimisation	High	High response
REMIND	2100	General equilibrium	Intertemporal optimisation	High	High response
TIAM-ECN	2100	Partial equilibrium	Intertemporal optimisation	High*2	High response*2
WITCH	2100	General equilibrium	Intertemporal optimisation	Low	Low response

*1 Classification represents a pattern of common model behaviour in response to a carbon tax in terms of cumulated carbon reduction, carbon over energy intensity reduction and structural changes in energy use (primary energy) (Kriegler et al., 2015).
*2 The TIAM-ECN model was not part of the Kriegler et al. (2015) evaluation study – based on the model characteristics for the TIAM-ECN model it is assumed that it behaves similarly to comparable models.

By combining the models in an inter-comparison study, the robustness of the projected long-term developments may be tested. Multi-model inter-comparison studies are therefore a means to reflect on key structural uncertainties through the diversity of participating models and assumptions about future change. Outcomes that are found to be rather similar under a cross-model comparison are therefore considered as more robust (Tavoni et al., 2015). Based on this, this study will focus on the collective pattern observed through the seven IAMs rather than the individual model responses. The model responses of the selected seven IAMs show to produce a variety of result for technological deployment, while broadly following similar emission reduction pathways (see Figure A1 in Annex I). This implies that no specific model response is visibly overrepresented in the pool of IAMs.

4.2.1.2 Scenarios

We analyse two different scenarios in this study describing futures with and without climate policy. These scenarios have been developed as part of the multi-model LIMITS project, which aimed at assessing policies and timescales consistent with limiting global mean temperature increase by 2°C target within the 21st century under a diverse set of future assumptions (Kriegler et al., 2013). The IAMs participating in this project solely harmonised assumptions on the presence or absence of future climate policy.

1. The baseline (*Baseline*) scenario describes a business-as-usual case in which there will be no global agreement on international climate policy. Changes in the energy system will therefore mostly be driven by other factors than climate policy. In general

this leads to no major regime shift over time, allowing GHG emissions to increase with overall no global peak in CO_2 emissions and only late century peaking of total GHG emissions (see Tavoni et al. (2015); van Sluisveld et al. (2013) for regional and global decomposition analyses). A business-as-usual scenario allows to consider the course of system change without additional (exogenous) climate policy pressure.

2. The climate policy (*2 Degrees*) scenario describes a cost-optimal mitigation pathway that will restrict the global increase in temperature to a maximum of 2 degrees Celsius in the year 2100 (all corresponding to a likely (>66%) probability of meeting 2°C, see Figure A1 in Annex I). To maintain narrative simplicity, this idealised scenario assumes immediate and universal implementation of a global carbon tax. The carbon tax increases the relative price of energy carriers with carbon content, creating a price-based preference order that favours low-carbon or carbon-removal alternatives to unabated fossil-fuel technologies. In general this leads to an immediate move away from fossil-fuel dependent power supply technologies, while devising varying blends of the following options as part of the decarbonisation strategy: (1) constructing renewable non-combustible power capital stock, (2) deploying carbon removal technologies (such as carbon capture and storage, CCS) which allow for rapid emission reductions throughout the century and (3) energy efficiency. The difference between the *2 Degrees* and the *Baseline* scenario is the effect of a gradually increasing carbon tax under an effort sharing principle across the represented regions in IAMs.

4.2.2 Expert elicitation

Expert elicitation is an assessment method to unravel potential courses of development by consulting experts using a well-described elicitation protocol. Generally they are used to compile subjective probability distributions which reflect the beliefs of experts on the effect of endogenous and exogenous factors on future change (Bosetti et al., 2016). In this study we utilise expert elicitation as a method to collect alternative interpretations of future technological development under assumptions about the future presence or absence of climate policy (*Baseline* and *2 Degrees* scenarios).

4.2.2.1 Expert selection

To gain alternative insights into future developments we have selected experts with a comprehensive view of all the various factors that may stimulate or inhibit the development of a specific technology (both technical aspects, as well as whole energy system dynamics). To identify relevant participants, we drew on the lead authors of technology-focussed chapters of key assessment and synthesis products such as the

IPCC's *4th Assessment Report*[3] (Sims et al., 2007), the *Global Energy Assessment* (GEA, 2012), the IPCC's *Special Report of Renewable Energy Sources and Climate Change Mitigation* (Edenhofer et al., 2011) and the *Global Status Report* (REN21, 2014). We thus extended earlier selection procedures that identified relevant expertise. Each expert was contacted via email, explained the project aim, and invited to take part in the elicitation. To boost sample sizes, participating experts were also requested to propose alternative or additional participants following a snowball sampling technique. This network approach proved particularly useful for identifying bioenergy and nuclear experts in this study.

A total of 39 experts took part in our elicitation (33% of the 117 experts contacted), including representatives of universities or research institutes (51%), member-based organisations dedicated to a specific technology (21%), governmental agencies (15%), private sector (8%) and intergovernmental organisations (5%) (see Table 4-2, and Annex II). Overall, the participating experts formed a diverse group covering both theoretical and practical knowledge. Although there is no fixed rule determining the number of experts needed in elicitations, five to six specialists are considered to be a lower bound for representing most of the expertise and breadth of opinion, provided there is some homogeneity among experts in understanding the problem (Keeney and von Winterfeldt, 1991; Morgan, 2014). In total the number of experts sampled in this elicitation are in the range of comparable expert elicitations on future system change (see for an overview Bosetti et al. (2016)), though sits at the lower bound for each technology individually.

Table 4-2 - Overview of invited experts per technology

	Wind	**Solar**	**Nuclear**	**Biomass**	**CCS**
Number of experts contacted	24	19	16	33	25
Responses	7 (29%)	7 (37%)	6 (38%)	12(36%)	7 (28%)
Year of elicitation	2014-2015	2014-2015	2014-2015	2014-2015	2015-2016
Academia / research institutes	2	3	3	6	6
Governmental agency	1	2	1	1	1
Intergovernmental organisation			2		
Member-based organisations	3	1		4	
Private owned	1	1		1	
TOTAL	7	7	6	12	7

3 During the design of the elicitation protocol the IPCC AR5 WGIII report was not yet published.

4.2.2.2 Elicitation method

In the elicitation, we used both direct and indirect elicitation methods, requiring the experts to express both quantitative estimates (e.g., a lower and upper bound and a best estimate) and a qualitative evaluation (e.g. via ranking and expressing perception). These different approaches were used to identify possible cognitive biases. Recognised biases in expert elicitations are (1) motivational biases (due to personal interests or other context-related factors), (2) accessibility biases (relating to information coming first to mind), (3) anchoring and adjustment biases (not being able to adjust above or below a benchmark or reference point), and (4) overconfidence bias (as a result of reinforcing evidence found in newly available information) (Martin et al., 2012).

The first two types of bias may be limited via the framing of questions. In order to expose motivational bias, the survey started with a question where experts were asked to rank the contribution of their technology to total electricity supply within a subset of eight technology families under varying future pathways for 2050. This question functioned as a self-assessment, providing insights on potential biases within a particular group of technology experts compared to the group as a whole. To reduce accessibility biases, we selected and pre-tested metrics based on literature (van der Zwaan et al., 2013; van Sluisveld et al., 2015; Wilson et al., 2012) to ensure their familiarity to both the IAM community and the technology experts. The selected metrics, covering both technology stock and growth over different timescales, are depicted in Table 4-3.

Table 4-3 - overview of aggregate system metrics included in the expert elicitation

Group	Metric	Description
Wind **Solar** **Nuclear** **Biomass**	Total installed capacity (GW)	Describing the total amount of technology stock
	Share in total electricity (%)	Describing the contribution of a technology to the electricity mix
CCS	CO_2 capture rate ($MtCO_2$/yr)	Describing the total capture capacity in the power sector
	Share in total electricity (%)	Describing the contribution of a technology to the electricity mix

Anchoring and overconfidence biases are harder to overcome given the unfamiliar nature of long-term future development. In order to test the consistency and robustness of experts throughout the elicitation protocol, several methods have been devised. First, to limit overconfidence and anchoring (Morgan, 2014), we asked experts to provide a lower limit, mean and upper limit expected value, instead of point estimates, for future developments under different climate policy assumptions and for different periods in time. Additionally, the experts were asked to provide these quantitative values before they were shown the average value from all IAM projections combined. Secondly, 'rephrasing with alternative wording' is another suggested remedy for these biases (Martin et al., 2012; Morgan, 2014). Instead of asking the same questions multiple times in different wording, we have opted to ask about two different metrics that are logically interconnected, with (1) total installed capacity containing information about technology stocks and growth, and (2) market share providing information on the impact on the electricity system. Eliciting both metrics can be considered as alternative ways to ask about future technological change in the power sector.

In a later stage of the survey, the experts were presented with a visual representation of the average of IAMs outcome on the same set of metrics. As another means to test for consistency we asked the experts to assess the presented values via the use of a five-point Likert scale, with options to assess the IAM outcome as "very low" to "very high" with three evenly distributed intermediate steps in between. Although Likert scale results cannot reflect the breadth of possible response in much depth, they are preferred over "open questions" as they allow for quick sampling and responses are logged as integer numbers. This method thus yields standardised output which improves the comparability between experts and expert groups. To avoid forced choice, the survey also offered the option to opt out of the question. For all questions, the experts could also provide (optional) comments to explain their reasoning (see Annex III for example questions and build-up).

We administered the survey online for experts to self-complete in their own time. One limitation of online surveys is that it is hard to know whether the question was understood correctly by the experts, or whether the experts took shortcuts to complete the survey faster, leading to less reliable responses or missing data (Baker et al., 2014). However, the advantages of online surveys include geographical flexibility, cost-effectiveness and the option for participants to take the survey at any time and place of choice. Moreover, the surveys were carried out after an initial pre-test with an expert in each technology domain. The pre-test aimed to test the clarity of the questions, as well as to consider whether questions are interpreted similarly across various technology expert groups. The pre-test confirmed an overall understanding of the metrics presented in Table 4-3.

4.2.2.3 Overall structure of the survey

The surveys have been carried out between September 2014 and June 2016 and started out by asking experts to rank the relative roles of various technologies by their importance (in terms of share in total power supply by 2050). This question was asked to all experts (thus requiring them to also assess technologies other than their own expertise). Results will be further discussed in section 4.3.1.

Next, the elicitation groups were guided through a two-step approach, starting out with formulating quantitative estimates (lower, mean and upper estimates) for the metrics shown in Table 4-3. The experts were asked to estimate each metric for both the near-term (2030) and medium-term (2050) under both *Baseline* and *2 Degrees* assumptions. In a subsequent step, the elicitation groups were asked to evaluate technology projections provided by IAMs using the same metrics. In this instance, the experts could assess the presented IAM values for near-term (2030) and medium-term (2050) projections under *Baseline* and *2 Degrees* assumptions and rate the value as "very low", "low", "reasonable", "high" or "very high". The results of this two-step approach are further discussed in section 4.3.2.

4.3 Results

4.3.1 Comparing power supply system projections

In the first part of the comparative analysis we focused on the relative contribution of specific energy technologies to total electricity supply under *Baseline* and *2 Degrees* policy assumptions by 2050. For experts, ranking the energy technology based on their contribution to future energy systems has been an explicit question. For IAMs, a similar ranking has been constructed by assigning ranks to the average relative contribution to total power supply (with the largest relative contribution receiving the number one position, the second largest relative contribution the second position, etc.). Results are presented in Figure 4-1, plotting the mean and spread of expert rankings (y-axis, representing the 15th and 85th percentile of 39 responses) versus the mean and spread from IAM projections (x-axis, representing the breadth of outcomes of 7 IAMs). A diagonal line is added to the graph to represents the position in the plot where experts and IAMs are in consensus about the relative position of an energy technology in a future power supply. A 1-point margin of difference is considered as broadly in agreement as well (dashed area in Figure 4-1).

We find that IAM and expert results are broadly consistent regarding the role of different technologies in 2050 under business-as-usual conditions (*Baseline*, left hand side panels). Both IAMs and experts expect fossil fuels to remain the dominant technology, followed by electricity supply via intermittent technologies (in particular wind). Some differences are found for the relative position of the solar and nuclear energy supply technologies, showing that experts have a greater preference for solar energy, whereas IAMs show a greater preference for nuclear power. Overall, the expert responses reach a wider range in results than IAMs, which could be a reflection of the more singular representation of technology diffusion in IAMs (i.e. techno-economic, therefore accounting for a narrower set of drivers and barriers of technological change) than represented in the different views of experts.

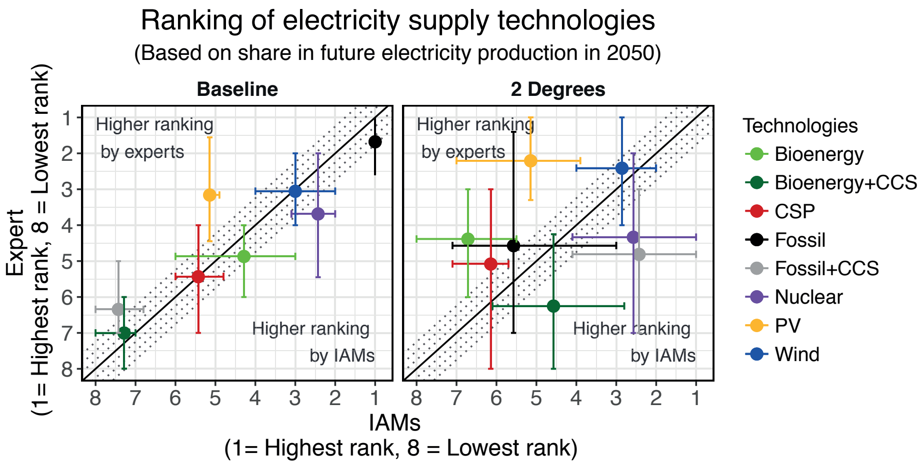


Figure 4-1 – Mean ranking of energy technologies in the energy system in 2050 for both the experts and IAMs. Rank 1 is the technology with the largest electricity supply, rank 8 the lowest. The presented ranges are based on the outcomes of 7 IAMs and 39 experts. For experts the range represents the 15th and 85th percentile of the outcomes. Diagonal line indicates agreement, whereas the shaded area represents a range of max 1-point difference.

Under stringent climate policy considerations (*2 Degrees,* right hand side panels) there is a very noticeable difference between IAMs and expert ranking as data points move further away from the diagonal line. This deviation is also noticeable among the experts and among the IAMs themselves (reflected by an increasing spread). IAMs tend to rank fossil+CCS, bioenergy+CCS and nuclear technologies to a higher position than experts (all relatively large unit-scale technologies), whereas experts tend to give higher scores for solar power (both photovoltaic (PV) and concentrated solar power (CSP)) and bioenergy (both technologies that can be implemented on a more decentralised and distributed basis). A major contrast between IAMs and experts is observed in the deployment of bioenergy, whose position directly relates to the choice of models to favour bioenergy+CCS. Wind power shows to be the one exception, showing an overall consensus between experts and IAMs on its relative position, which could be a result of the large experience base for large-scale wind energy deployment and a stable growth over decades.

4.3.2 Individual technology projections and evaluations

In the next step the expert groups have been asked to provide quantitative estimates for their short (2030) to medium (2050) term expectations for the metrics presented in Table 4-3. In Figure 4-2 we depict the range of outcomes for the *Baseline* scenario and in Figure 4-3 for the *2 Degrees* scenario. For comparison, we portray elicited results together with IAM outcomes. Both figures utilise boxplots for visualising information, allowing to add weight to clusters of data points (shown by the box, or interquartile range) while values that are more distant, though in close proximity of the cluster, are highlighted in the whiskers of the plot. Next to a visual representation we employ a simple statistical test to consider whether the differences between IAM and (mean) expert estimates are significant. For this, the Welch's t-test is used to test the hypothesis whether the means of two groups are equal for samples with unequal sample size and unequal variance. Although t-tests assume normality in the samples, which may not be entirely considered appropriate in expert elicitation (Bosetti et al., 2016) or IAM assessment, they are mainly used in this study to draw insights on the consensus or diversity in the provided estimates (with a high *p*-value implying consensus and low *p*-value diversity). In a subsequent step, the experts have been confronted with the mean results of IAMs and have been asked to qualitatively evaluate the values from "very low" to "very high" with three intermediate steps in between. The combination of (1) the quantitative estimates, (2) the Welch's t-test and (3) the qualitative evaluation allows for a thorough comparison of IAM results with the views of the experts.

Under *Baseline* assumptions (see Figure 4-2), the experts reported overall higher estimates for installed capacity than projected by IAMs, with nuclear as an exception. This systematic difference can be observed for both the 2030 and 2050 period. Particularly solar PV shows substantially higher estimates in the expert projections than considered in the IAM projections, displaying an approximately seven-fold higher estimate for installed capacity in 2030 and a twenty-fold difference in 2050 (assuming median values, see also Annex V). For the share in electricity, the experts are also found to assign significantly greater roles to solar PV than assumed by IAMs, which corresponds with Figure 4-1. A similar pattern can be observed for wind power, although at a different level of magnitude. Over time the discrepancy between experts and IAMs diminishes gradually, as can also be deducted from the increasing *p*-values in Figure 4-2.

The experts projected more conservative values for nuclear in the short-term, which may be a result of deviating assumptions on the economics and likelihood of new construction in the light of the expected retirement of existing capital in the coming decade (World Nuclear Association, 2016). Moreover, as seen in the share of nuclear in total electricity production the experts assume widely diverging futures of development for nuclear, which could lean towards the conservative side or progressive side of the spectrum. For biomass the IAMs reproduce a similar result as observed in Figure 4-1, showing only limited contribution and growth for this technology. In the *Baseline* scenario no growth or diffusion is considered for power sources combined with carbon capture and storage.

The experts provided overall consistent answers throughout the various elicitation methods (quantitative and qualitative assessment) – albeit with some minor differences due to different sample sizes between the methods (greater number of experts participated in the qualitative assessment) (see also Table F1 in Annex VI).

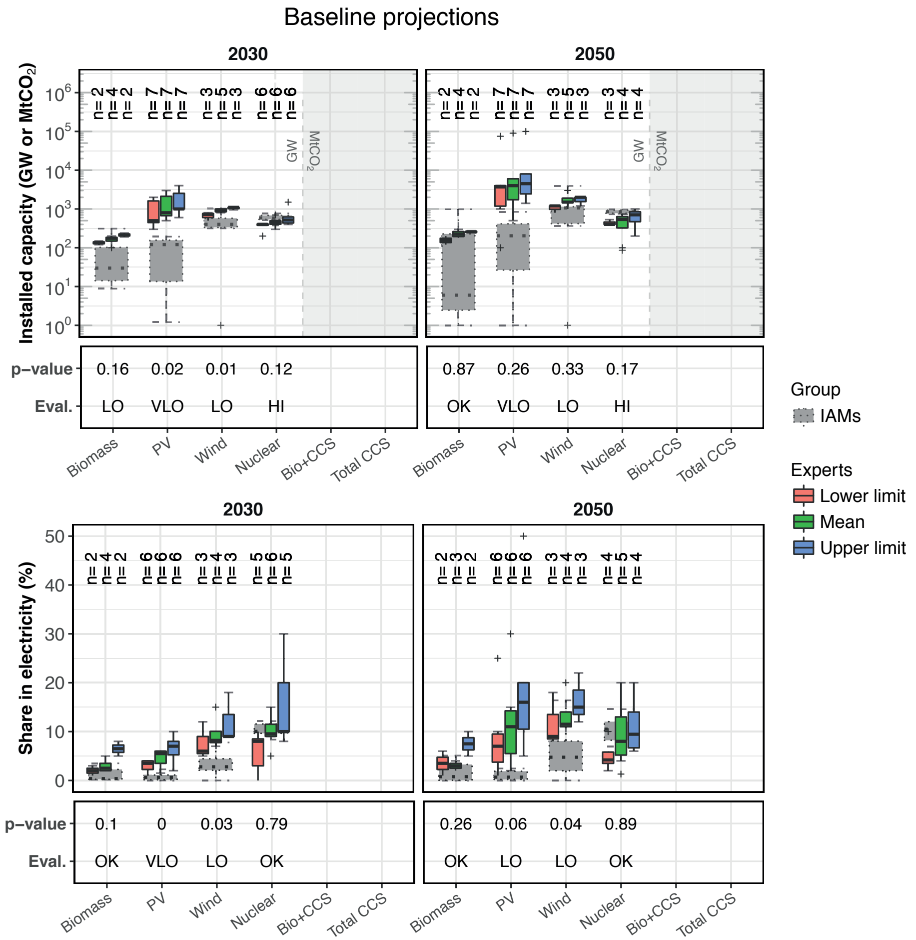


Figure 4-2 – Elicited indicators under *Baseline* assumptions by each technology specific expert group. Grey boxes represent IAM outcomes; the mean value is presented by a dotted line. The numbers at the top represent the number of actual elicitations per technology for the quantitative assessment. Experts were free to provide information for the lower, mean and/or upper limits, or opt out of quantifying future development altogether, resulting in different sample sizes than considered in table 4-2. The tabular overview contains the *p*-values of the Welch's t-test (*p*-value < 0.05 would imply highly unequal means (diversity), *p*-value > 0.95 would imply equal means (consensus)) and the average outcome of the qualitative assessment (Eval.) of IAM results (VLO: "Very Low", LO: "Low", OK: "Reasonable", HI: "High", VHI: "Very High". See Annex VI for further information). Under Baseline assumptions no growth and diffusion of technologies such as Bio+CCS and CCS in general are taken into consideration.

Under *2 Degrees* considerations, several differences between experts and IAMs are found, mostly confirming the earlier results found in Figure 4-1, noticing differences for the use of solar PV, Bio+CCS and Total CCS (see Figure 4-3). For solar PV, the growth and diffusion expectations are significantly different between experts and IAMs for both the short to medium term, which correspond with the findings in Figure 4-1. For CCS deployment, although the experts assume some CCS deployment to materialise, they show to be greatly divided in the extent to which this may materialise. This may be partly explained by the lack of actual experience in the (commercial) application of CCS and Bio+CCS technologies, as well as the large uncertainties surrounding the (joint) application (Fuss et al., 2014; Smith et al., 2016). Overall experts consider limited application before 2030 and expect that CCS is mostly limited to fossil-fuel based power plants over time (as opposed to the large projected contribution of Bio+CCS in 2050 by IAMs). Interestingly, the IAMs appear to be more-or-less in consensus on the depicted magnitude of CCS deployment.

Conversely, we find that some agreement has been established between the estimates of experts and IAMs under *2 Degrees* considerations. This is particular observed for wind power on the short-term, showing that IAMs approximate the estimates of experts more accurately than depicted earlier under *Baseline* considerations (as shown by the *p*-value and the "reasonable" [OK] evaluation for installed capacity). However, the share in power production is considered rather low. This would imply that experts are more optimistic about the expected contribution of wind power to total power supply under *2 Degrees* than considered by IAMs for a similar capital stock. Some convergence between expert and IAM estimates is also found for bioelectricity. Experts articulated that biomass co-firing can be very effective as it can be installed relatively quickly and retrofitted into existing capital, though they stressed simultaneously that additional incentives are necessary to move biomass into power generation and away from other applications. As such, the experts and IAMs are in agreement over the short-term estimates (2030), but start to diverge when moving out towards 2050. However, given the contrasting views on the contribution of bioelectricity in total electricity production for 2050 (Figure 4-1), the observed difference in scale and perception (or "high" [HI] evaluation) reveal a more structural discrepancy on the presumed availability and economics of bioenergy use in power generation between experts and IAMs.

Despite visually overlapping estimates for nuclear energy, no significant or consistent difference or agreement can be observed between experts and IAMs. Both provided higher estimates over the short-term than assumed under *Baseline* considerations, employing implicit assumptions on new build capacity. Despite a greater tendency in IAMs to utilise nuclear energy in the electricity mix (Figure 4-1), the estimated shares are considered as relatively equal between experts and IAMs. Again, it should be noted that experts provided overall reasonably consistent answers throughout their quantitative and qualitative evaluation of future technological deployment.

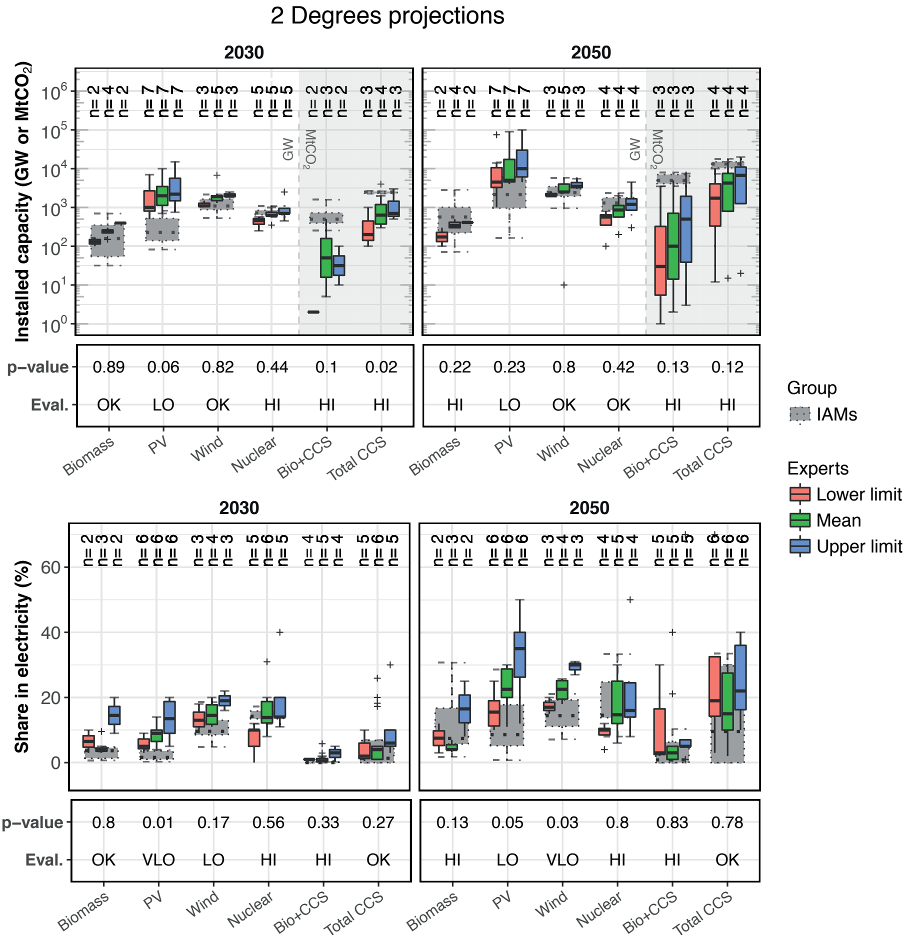


Figure 4-3 - Elicited indicators under *2 Degrees* assumptions by each technology specific expert group. Grey boxes represent IAM outcomes. The numbers at the top represent the number of actual elicitations per technology for the quantitative assessment. Experts were free to provide information for the lower, mean and/or upper limits, or opt out of quantifying future development altogether, resulting in different sample sizes than considered in table 4-2. The tabular overview contains the *p*-values of the Welch's t-test (a *p*-value < 0.05 would imply highly unequal means (diversity), whereas a *p*-value > 0.95 would imply equal means (consensus)) and the average outcome of the qualitative assessment of IAM results (VLO: "Very Low", LO: "Low", OK: "Reasonable", HI: "High", VHI: "Very High". See Annex VI for further information).

4.4 Discussion

In this study we have compared the expectations of experts to the projections of IAMs to identify whether IAM projections diverge in systematic ways from expert interpretations of future developments. Several differences have been highlighted in terms of technology deployment and projected growth. Interestingly, some of the observations align with the standing debate on IAM results.

An important aspect in interpreting the results is time. Both experts and models are exposed to information on long-term historical trends (e.g. last thirty years) and short-term historical trends (e.g. last five years). As models are designed to depict future change over long time horizons, they are often calibrated against long-term historical patterns of change (see also van Vuuren et al. (2010)) with some years between each calibration cycle. This means that IAMs are less sensitive to short-term volatility, but may embed some system inertia in their projections. In fact, more recent model projections seem to have moved towards higher use of renewable energy technologies (see e.g. Pietzcker et al. (2016)) – but still do not reach similar deployment levels as presented by the experts in this study. Experts, on the other hand, may pick up new information more easily which could have influenced their views on potential future change. For example, unprecedented growths per subsequent year may reinforce experts to provide a higher estimate on future growth. Wind (showing a higher annual growth rate than the cumulative sustained growth over the last decade, see Global Wind Energy Council (2015)) and PV (IRENA, 2016) might have been particularly liable to overconfidence biases (which has been observed to some degree in this study, see Figure D1 in Annex IV). Such continued growth in renewable energy technologies, or a potential wave of interest in emerging technologies (Melton et al., 2016), and the continued absence of large-scale CCS demonstration projects, are very salient developments for experts to convey different responses than provided by IAMs.

A second aspect is the role of simplification. In order to assess global developments over time in a consistent and structured framework, several necessary simplifications of complex real-world processes need to be adopted in IAMs. As a result, IAMs are inherently compromising their system representativeness and their reflection of current trends and developments. In some cases, one might argue that this means that models do not accommodate the breadth of possible transition pathways to be considered under *Baseline* or *2 Degrees*. Indeed, experts have articulated specific roles for technologies and policy measures during the ranking assignment (Figure 4-1) that models typically do not reproduce, such as decentralised power systems. This more narrow focus in IAMs, or recognised ignorance (Beck, 2017; Walker et al., 2003), is created by a difficulty to translate certain processes into a representative cost-benefit formulation that can be fitted into models. As this is the case for more decentralised alternatives, this may result into some bias in IAMs towards the more large-scale, centralised, technologies. At the same time, one may also argue that experts lack the system focus of models.

A third aspect that should be noted is the inherent structural uncertainty in future change and the limitations in capturing system processes in (representative) quantitative values. IAM projections are able to devise explicit conditions that deviate from more likely developments (e.g. immediate global action). These projections will be more difficult to compare with expert estimations who will reason more from likely developments. As the *2 Degrees* scenario reflects an idealised best-case scenario with immediate global action in the IAM interpretation, it represents optimal conditions that are not to be expected to materialise anytime soon in the real-world. If more likely assumptions about future change would have been adopted into the scenario architecture of IAMs (e.g. policy delay, less optimistic assumptions on CCS) it would have resulted into higher deployment levels of renewable energy technologies than currently presented in this study (see for example, Eom et al. (2015); Luderer et al. (2014); Riahi et al. (2015)).

Finally, a structural discrepancy was found for the considered contribution of bioenergy to power supply. Experts articulated an explicit need for policy to move biomass into power generation. Interestingly, Calvin et al. (2013) found that IAMs also dedicate a larger share of biomass resources to liquid fuel production than to power generation. This difference of scale thus underlines a disagreement on the availability and economics of mitigation alternatives in the liquids and electricity production sectors between experts and IAMs.

4.5 Conclusion

In this study, we compared the outcomes of IAMs to the estimates of experts to systematically compare both insights on future technology deployment. We have included answers of 39 experts divided over 5 technology families under two different climate policy scenarios for the near (2030) and medium (2050) term. Subsequently we asked the participating experts to evaluate the values as projected by IAMs under similar climate considerations and timeframes. The main conclusions of this analysis are:

Experts and IAMs are broadly in agreement on the development of power system change and technological diffusion over time under Baseline considerations.

The study exposed agreement among the experts and IAMs on the direction of status-quo system change (*Baseline*) over time. All experts (and IAMs) consider fossil fuels the major power source if climate policy is absent, with some contribution of renewable power sources. A difference between IAMs and experts is found in the estimated magnitude for technologies over time, showing to be structurally higher for renewable energy technologies. The systematically higher estimates by experts for installed capacity cannot be entirely explained via the current analysis.

Under 2 Degrees considerations, the considered development of power system change, technological growth and diffusion estimates are diverging within and between the experts and IAMs.

Although some convergence occurs between the estimates of experts and IAMs under *2 Degrees* considerations, several structural differences in perspective have come to light. Overall, experts assume a larger contribution of renewable energy alternatives in combination with fossil fuel in the power system by 2050, whereas IAMs are more likely to deploy nuclear and thermal power plants with carbon removal technologies over time. Moreover, the role of bioenergy in the power system shows to be a defining element in the type of *2 Degrees* pathway being considered. The experts consider a potential role for bioenergy in mitigation strategies if deliberate choices are made to utilise this resource in power production, while IAMs only consider, and gradually depend on, the combined use of bioenergy with carbon capture and storage. Deviations in the estimated magnitudes for the technologies can be partly attributed to different expectations in the availability and economics of the considered mitigation technologies, though several additional challenges and drivers may be underlying the adoption of specific mitigation technologies in a *2 Degrees* pathways over time. It should also be noted that the required transition in a 2°C-constrained world leads to a break from currently known trends, explaining partly for the higher level of uncertainty.

Expert elicitation may provide useful feedback to IAMs on generating more representative mitigation strategies

Expert elicitation provides useful information to detect several market uncertainties that are not explicitly represented in IAMs. Devising multiple analytical perspectives in a comparative study may thus be a useful means to evaluate projections and interpretations of future development under varying assumptions. As such, future research could focus more on the systematic differences found between future projections and interpretation by (1) pursuing a wider spectrum of system development in IAMs, as well as (2) consider more context-inclusive pathways as opposed to cost-optimal pathways to gain better insights on more plausible future pathways.

Acknowledgements

The research leading to these results has received funding from the European Union's Seventh Framework Programme FP7/2007-2013 under grant agreement n° 282846 (LIMITS) and n° 603942 (PATHWAYS). CW acknowledges funding support from the European Union's Seventh Framework Programme FP7/2007-2013 under grant agreement n° 308329 (ADVANCE). BvdZ acknowledges the financial assistance from the European Union's Horizon 2020 Programme under grant agreement n° 642260 (TRANSrisk). The authors are indebted to all contributing technology experts for partaking in this research. We would also like to thank Hilke Rösler for her research assistance.

Annex I: Overview of IAM responses

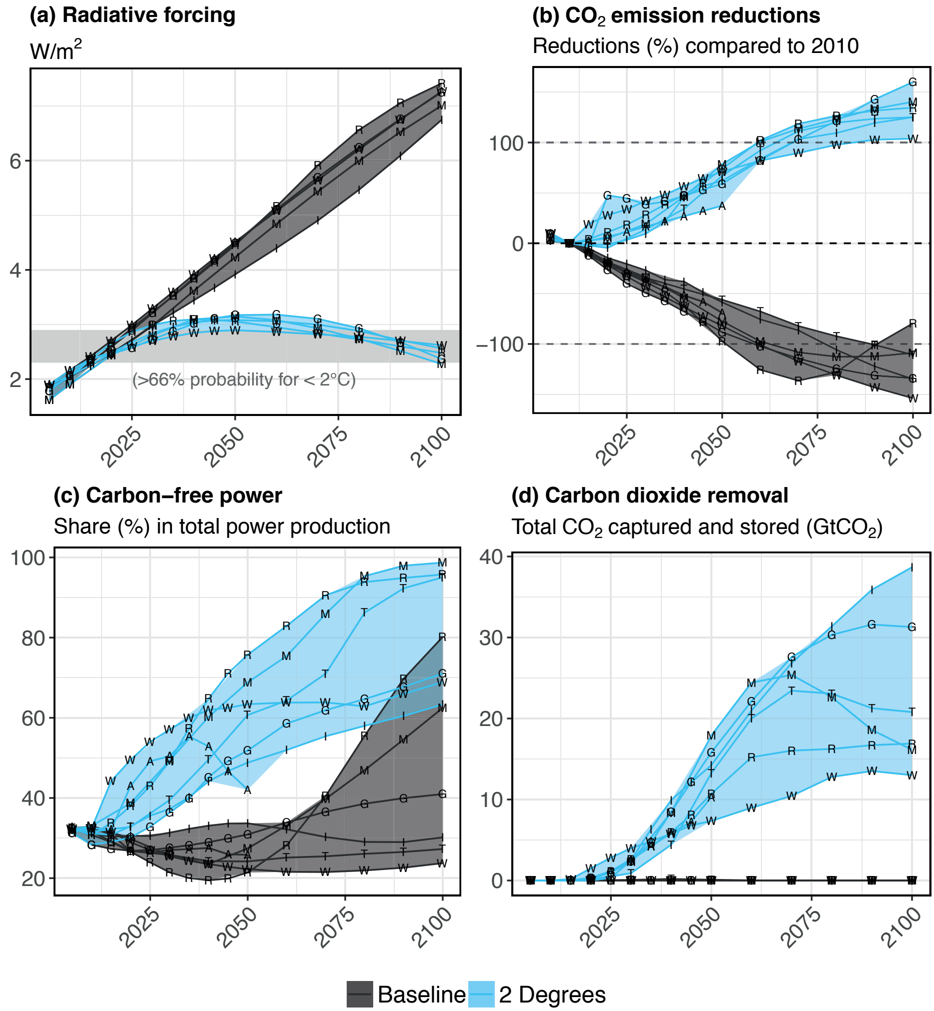


Figure A1 - Overview of a selected few scenario outcomes in a multi-model setting. Letters indicate the trajectory of the included IAM (A: AIM-EndUse, G: GCAM, I: IMAGE, M: MESSAGE, R: REMIND, T: TIAM-ECN, W: WITCH). Panel (a) includes radiative forcing from all greenhouse gases and forcing agents (including contributions from albedo, nitrate, and mineral dust). Panel (b) depicts total CO_2 emission reductions, reaching negative emissions between 2060-2075. Panel (c-d) depict the decarbonisation strategies assumed for predominantly power production (showing aggregated share of all non-biomass renewable technologies and nuclear power in panel C). Low shares of carbon free power production are compensated with high carbon dioxide removal rates (e.g. IMAGE, I).

Annex II: Participants and affiliations

Table 4A – Overview table of participating experts, categorised by survey group

Name	Contact	Group
Berndes, Goran	goran.berndes@chalmers.se	Biomass
Haara, Karin	karin.haara@worldbioenergy.org	Biomass
Junginger, Martin	h.m.junginger@uu.nl	Biomass
Smith, Pete	pete.smith@abdn.ac.uk	Biomass
Fritsche, Uwe	uf@iinas.org	Biomass
Slade, Raphael	r.slade@imperial.ac.uk	Biomass
Wellinger, Arthur	wellinger@triple-e-und-m.ch	Biomass
Dehue, Bart	bart.dehue@nuon.com	Biomass
Rauner, Sebastian	sebastian.rauner@ufz.de	Biomass
Chum, Helena	Helena.Chum@nrel.gov	Biomass
Saygin, Deger	DSaygin@irena.org	Biomass
Hughes, Alison	alison.hughes@uct.ac.za	Biomass
Ramana, M.V.	ramana@princeton.edu	Nuclear
H. Kim, Son	skim@pnnl.gov	Nuclear
Rogner, Holger	rogner@iiasa.ac.at	Nuclear
Gritsevskyi, Andrii	A.Gritsevskyi@iaea.org	Nuclear
Katsuta, Tadahiro	tkatsuta@kisc.meiji.ac.jp	Nuclear
Bunn, Matthew	matthew_bunn@harvard.edu	Nuclear
Lenardic, Denis	contact@pvresources.com	PV
Jager-Waldau, Arnulf	arnulf.jaeger-waldau@ec.europa.eu	PV
van Sark, Wilfried	W.G.J.H.M.vanSark@uu.nl	PV
Rekinger, Manoel	m.rekinger@epia.org	PV
Philipps, Simon	simon.philipps@ise.fraunhofer.de	PV
Mayer, Johannes	johannes.nikolaus.mayer@ise.fraunhofer.de	PV
Arvizu, Dan	dan_arvizu@nrel.gov	PV
Wiser, Ryan	RHWiser@lbl.gov	Wind
de Jager, David	d.dejager@ecofys.com	Wind
Infield, David	david.infield@eee.strath.ac.uk	Wind
Sinden, Graham	graham.sinden@trinity.oxon.org	Wind
Shukla, Shruti	shruti.shukla@gwec.net	Wind
Jensen, Peter	peter.hjuler@risoe.dk	Wind
Sawyer, Steve	steve.sawyer@gwec.net	Wind
Abanades, Juan Carlos	abanades@incar.csic.es	CCS
Van den Brink, Ruud	vandenbrink@ecn.nl	CCS
Berghout, Niels	N.A.Berghout@uu.nl	CCS
Ramirez Ramirez, Andrea	C.A.Ramirez@uu.nl	CCS
Kuramochi, Takeshi	t.kuramochi@newclimate.org	CCS
Lupion, Monica	m.lupion@ciuden.es	CCS
Herber, Rien	rien.herber@rug.nl	CCS

Annex III: Survey questions

Training for "quantitative expert projections"

Throughout the survey, we will make use of two possible global scenarios: one without additional global climate policy (A) and one with a stringent global climate policy (B):

Scenario	Description
A	A "no climate policy" baseline ('business as usual'). In this scenario, we assume there will be no new global agreement on international climate policy. The energy system will therefore mostly be driven by factors other than climate policy.
B	Stringent and immediate global climate policy. We assume that stringent climate policies are introduced worldwide in the short term in order to achieve a 50% reduction in global emissions by 2050, with the aim of restricting climate change to a maximum of 2 degrees Celsius.

Snapshot of self-assessment/ranking questions (example shown for only scenario A)

Please rank the following electricity generation technologies in order of their contribution to total global electricity production in 2050 (with rank 1 being the highest and 8 the lowest) for a scenario with no new climate policy (*scenario A*).

	1	2	3	4	5	6	7	8	× Don't know
Wind Energy	○	○	○	○	○	○	○	○	○
Photovoltaics (PV)	○	○	○	○	○	○	○	○	○
Concentrated Solar Power (CSP)	○	○	○	○	○	○	○	○	○
Nuclear Energy	○	○	○	○	○	○	○	○	○
Bioenergy	○	○	○	○	○	○	○	○	○
Bioenergy + CCS	○	○	○	○	○	○	○	○	○
Fossil Fuels	○	○	○	○	○	○	○	○	○
Fossil Fuels + CCS	○	○	○	○	○	○	○	○	○

[optional] Please add any comments to help us interpret your responses.

Snapshot of quantitative projection question (PV as example, total installed capacity)

Please provide your best estimates for the range of solar power (PV) installed capacity (in GWpeak) you think is feasible under for scenarios A and B in 2030 and 2050 (lower limit - mean - upper limit):

Installed capacity of PV (GWpeak):

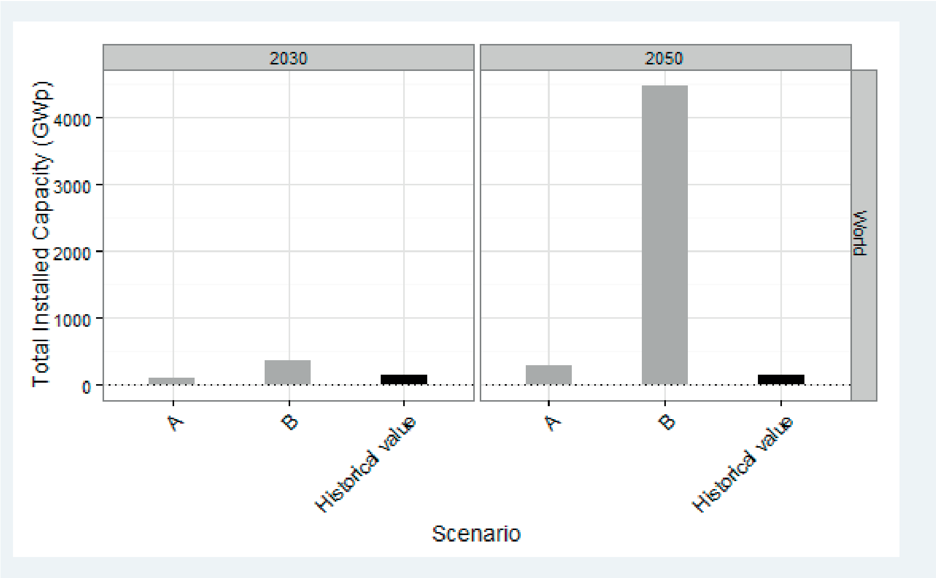
	Lower limit	Mean	Upper limit	Don't know
2030 Business-as-usual (A)				
2030 Stringent climate policy (B)				
2050 Business-as-usual (A)				
2050 Stringent climate policy (B)				

[optional] Please add any comments to help us interpret your responses (note that questions about important underlying factors are asked a few questions further)

Training for "qualitative evaluation of IAM projections"

In LIMITS, we have used global energy-environment models to explore the two scenarios introduced earlier, with different assumptions on global climate policy (see above for a description of the scenarios). The results of the different models vary greatly and the values shown are the means *. We would like you to assess the outcomes of this project. Here, we look at the installed capacity of PV installations on a global scale. For guidance purposes we have provided a recent historical reference point (EPIA, value in 2013).

* The depicted projection is the average of 7 global energy-environment models in the LIMITS project. If you would like to know more about the model assumptions, we would be happy to send you articles on the outcomes of the LIMITS scenarios.



Snapshot of qualitative evaluation question (PV example, total installed capacity)

How would you describe the presented value for PV capacity in scenario A with no new global climate policy?

	Very low	Low	Reasonable	High	Very high	Don't know
in 2030	○	○	○	○	○	○
in 2050	○	○	○	○	○	○

[optional] If the model projections from scenario A (no climate policy) deviate greatly from your estimates, please explain why.

Annex IV: Ranking of experts (group versus total)

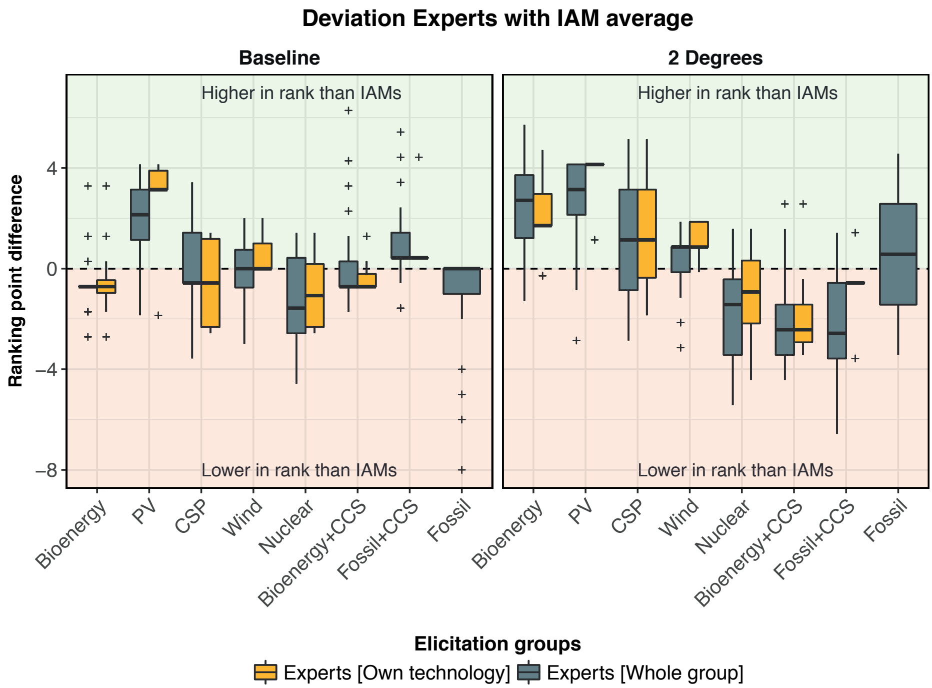


Figure D1 – Differences in ranking between various expert groups compared to IAM outcomes. A distinction has been made for the specific field of expertise and the group as a whole (based on 39 responses).

Annex V: Quantitative assessment: output boxplots (interquartiles only)

This annex provides the quantitative data as plotted in figures 4-2 to 4-3. The numbers provide the interquartile range of the boxplots and not the full range of articulated result. In the following sections the data is provided subsequently for (1) expert articulations and (2) IAM outcomes. The upper quartile (Q3) represents the 75th percentile of the data, the median represents the 50th percentile and the lower quartile (Q1) the 25th percentile. Additionaly, the mean value is presented for IAM data. The mean value has been presented to the experts to be used for qualitative assessment (Annex VI).

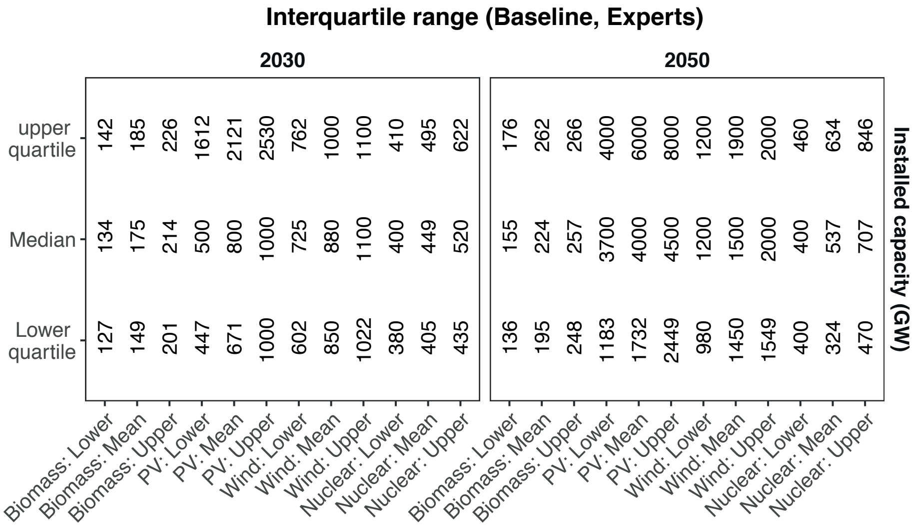


Figure E1 - Baseline: Installed capacity (GW), experts

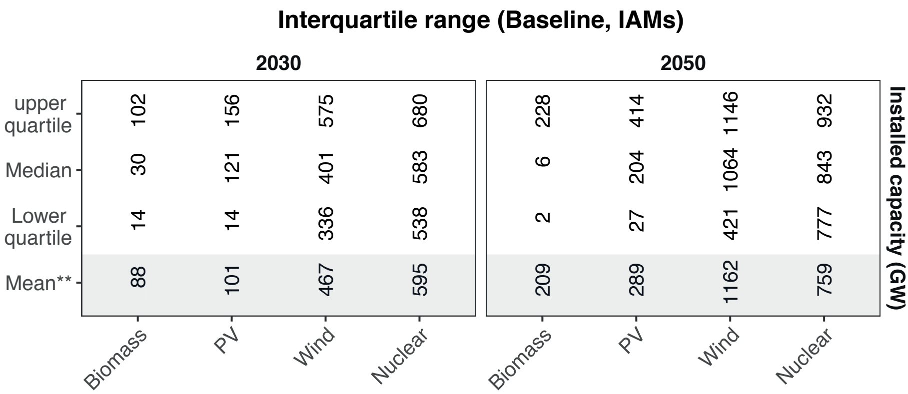


Figure E2 - Baseline: Installed capacity (GW), IAMs

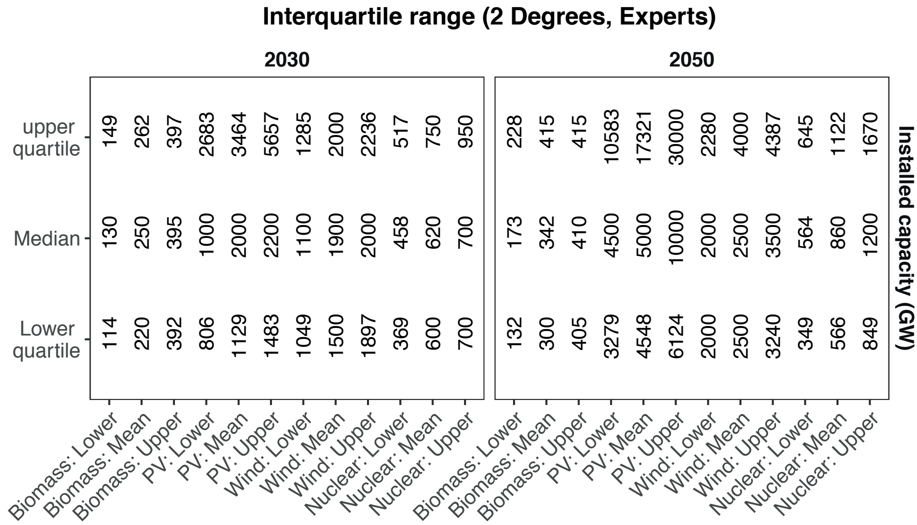


Figure E3 - 2 Degrees: Installed capacity (GW), experts

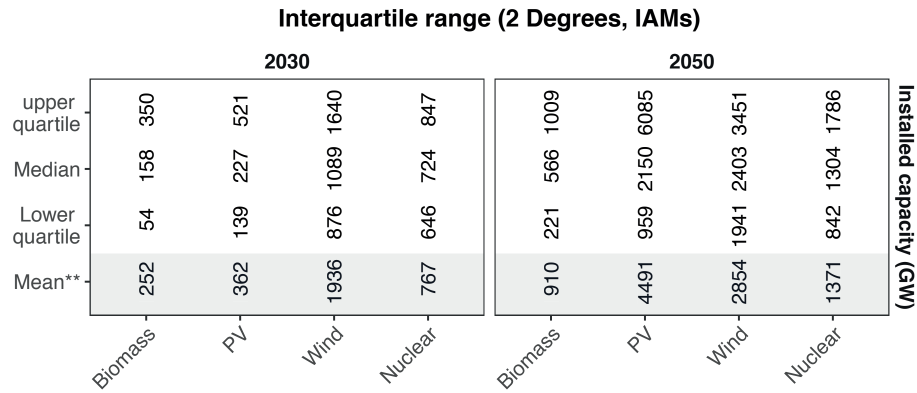


Figure E4 - 2 Degrees: Installed capacity (GW), IAMs

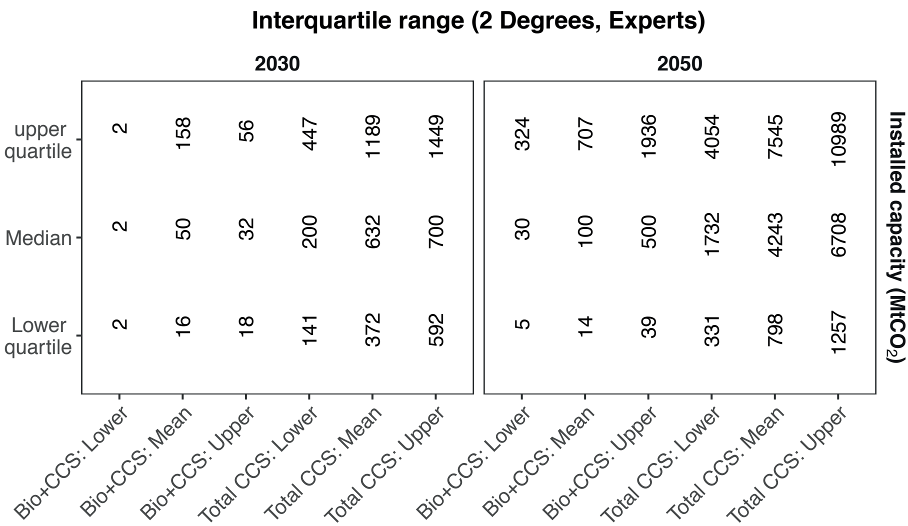


Figure E5 - 2 Degrees: Installed capacity ($MtCO_2$), experts

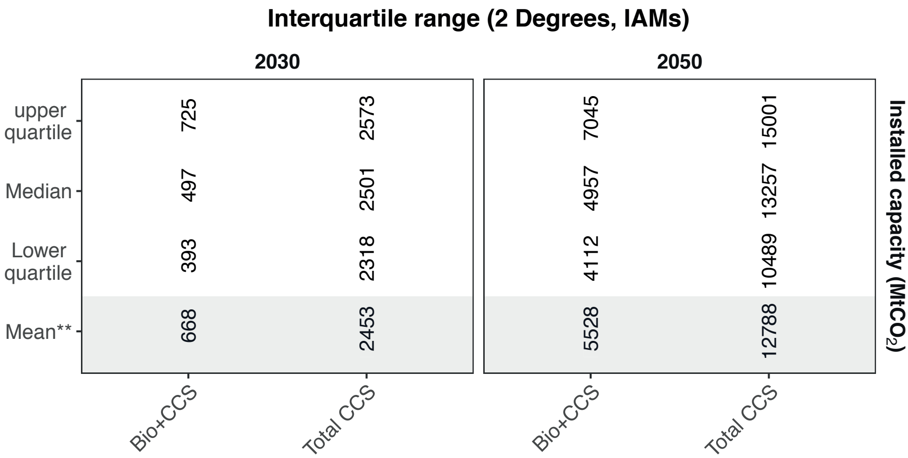


Figure E6 - 2 Degrees: Installed capacity ($MtCO_2$), IAMs

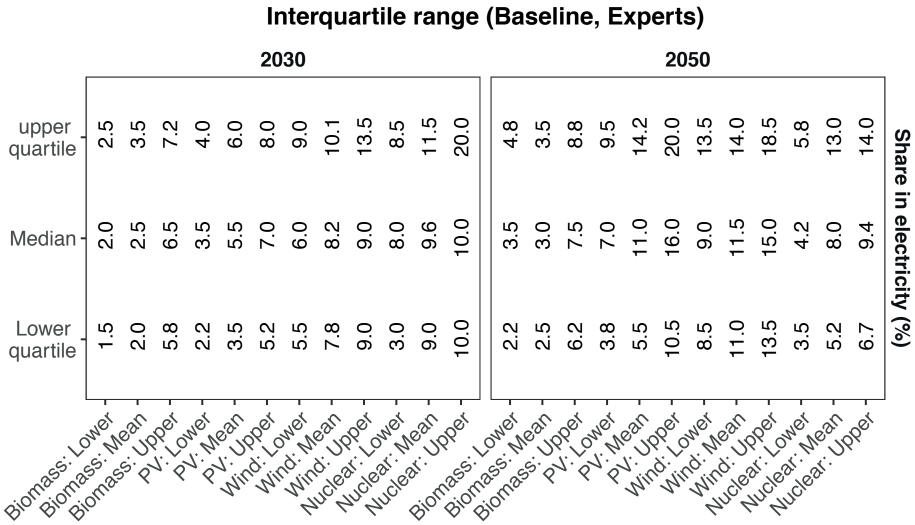


Figure E7 - Baseline: Share in electricity (%), experts

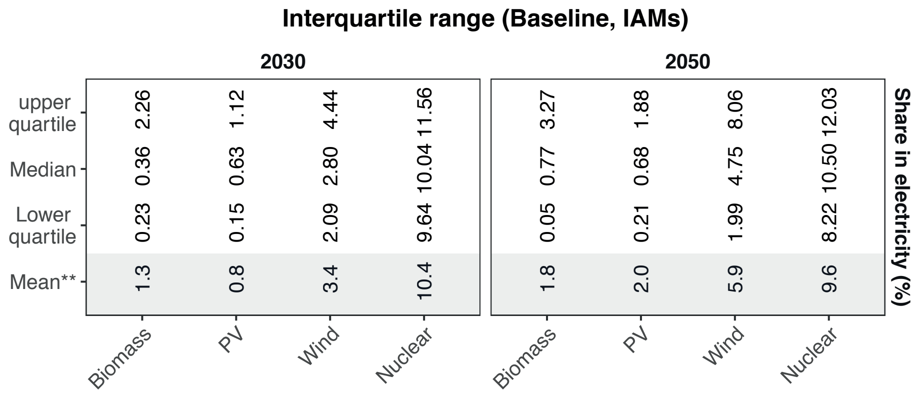


Figure E8 - Baseline: Share in electricity (%), IAMs

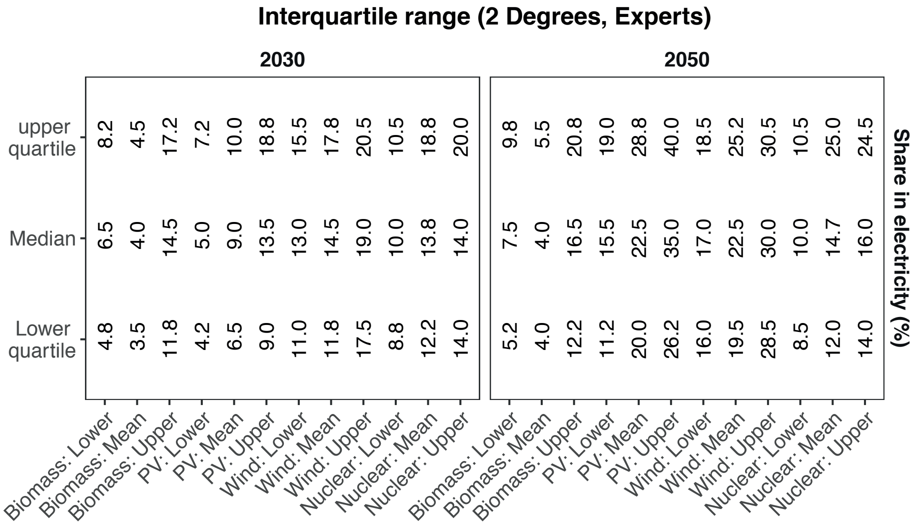


Figure E9 - 2 Degrees: Share in electricity (%), experts

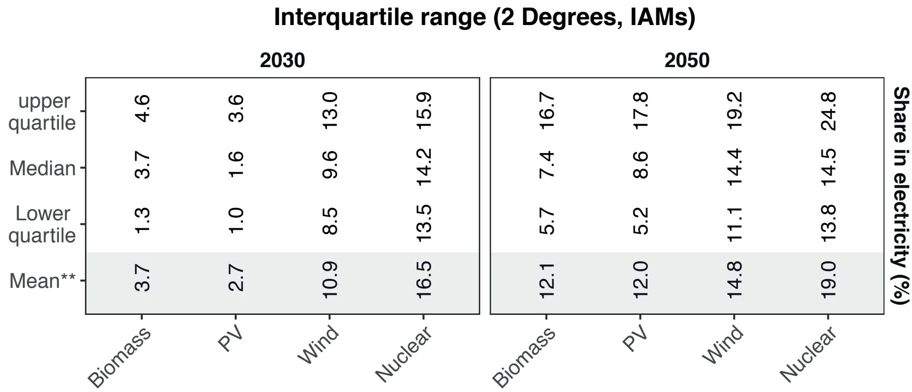


Figure E10 - 2 Degrees: Share in electricity (%), IAMs

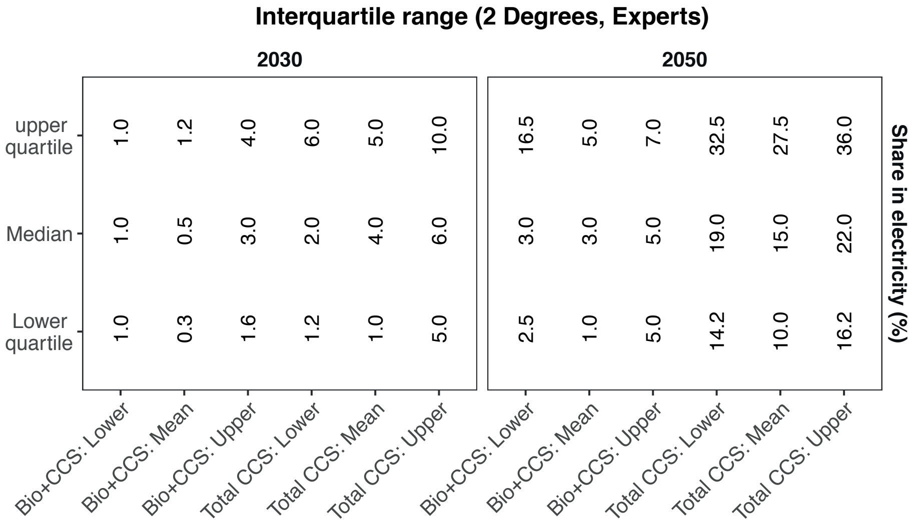


Figure E11 - 2 Degrees: Share in electricity (%), experts

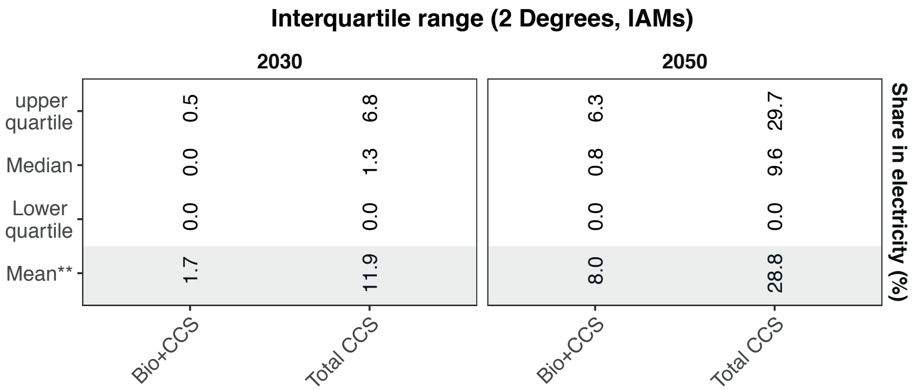


Figure E12 - 2 Degrees: Share in electricity (%), IAMs

Annex VI: Qualitative assessment: Transforming to numerical data and labels

For the qualitative assessment a 5-level Likert scale has been used (of which level 1 is representative of "too low", 2 as "low", 3 as "reasonable", 4 as "high" and 5 as "too high") which scores have been transformed into numerical data. The group of outcomes have been averaged to consider the overall score (see table F1).

Scoring legend:

1.0 –1.5 >> VLO (Very Low)
1.5 – 2.5 >> LO (Low)
2.5 –3.5 >> OK (Reasonable)
3.5 – 4.5 >> HI (High)
4.5 – 5.0 >> VHI (Very High)

Table F1- Numerical values for qualitatively evaluating the IAM results.

Technology	Scenario	Year	Indicator	Unit	IAM Average (assessed value)	Responses	Average score	label
PV	Baseline	2030	Installed capacity	GW	101	7	1.142857	VLO
Wind	Baseline	2030	Installed capacity	GW	467	6	1.666667	LO
Biomass	Baseline	2030	Installed capacity	GW	88	10	2.4	LO
Nuclear	Baseline	2030	Installed capacity	GW	595	6	4	HI
PV	2 Degrees	2030	Installed capacity	GW	362	7	1.571429	LO
Wind	2 Degrees	2030	Installed capacity	GW	1936	6	3.333333	OK
Biomass	2 Degrees	2030	Installed capacity	GW	252	10	3.1	OK
Nuclear	2 Degrees	2030	Installed capacity	GW	767	6	3.833333	HI
PV	Baseline	2050	Installed capacity	GW	289	7	1.285714	VLO
Wind	Baseline	2050	Installed capacity	GW	1162	6	2.166667	LO
Biomass	Baseline	2050	Installed capacity	GW	209	10	2.8	OK
Nuclear	Baseline	2050	Installed capacity	GW	759	6	3.833333	HI
PV	2 Degrees	2050	Installed capacity	GW	4491	7	2.428571	LO
Wind	2 Degrees	2050	Installed capacity	GW	2854	6	2.666667	OK
Nuclear	2 Degrees	2050	Installed capacity	GW	910	10	3.333333	OK
Biomass	2 Degrees	2050	Installed capacity	GW	1371	6	4.222222	HI
PV	Baseline	2030	Share in electricity	%	0.8	7	1.5	VLO
Wind	Baseline	2030	Share in electricity	%	3.4	6	1.6	LO
Biomass	Baseline	2030	Share in electricity	%	1.3	10	2.571429	OK
Nuclear	Baseline	2030	Share in electricity	%	10.4	6	3.4	OK
PV	2 Degrees	2030	Share in electricity	%	2.7	7	1.5	VLO
Wind	2 Degrees	2030	Share in electricity	%	10.9	6	2.2	LO
Biomass	2 Degrees	2030	Share in electricity	%	3.7	10	3.142857	OK

Table F1- Numerical values for qualitatively evaluating the IAM results. (continued)

Technology	Scenario	Year	Indicator	Unit	IAM Average (assessed value)	Responses	Average score	label
Nuclear	2 Degrees	2030	Share in electricity	%	16.5	6	3.8	HI
PV	Baseline	2050	Share in electricity	%	2	7	1.833333	LO
Wind	Baseline	2050	Share in electricity	%	5.9	6	1.6	LO
Biomass	Baseline	2050	Share in electricity	%	1.8	10	3	OK
Nuclear	Baseline	2050	Share in electricity	%	9.6	6	3.2	OK
Wind	2 Degrees	2050	Share in electricity	%	12	6	1.4	VLO
PV	2 Degrees	2050	Share in electricity	%	14.8	7	1.833333	LO
Biomass	2 Degrees	2050	Share in electricity	%	12.1	10	3.857143	HI
Nuclear	2 Degrees	2050	Share in electricity	%	19	6	3.6	HI
Bio+CCS	2 Degrees	2030	Installed capacity	$MtCO_2$	668	7	4	HI
Total CCS	2 Degrees	2030	Installed capacity	$MtCO_2$	2453	7	3.714286	HI
Bio+CCS	2 Degrees	2050	Installed capacity	$MtCO_2$	5528	7	4.285714	HI
Total CCS	2 Degrees	2050	Installed capacity	$MtCO_2$	12788	7	3.714286	HI
Bio+CCS	2 Degrees	2030	Share in electricity	%	2	7	4	HI
Total CCS	2 Degrees	2030	Share in electricity	%	12	7	3.142857	OK
Bio+CCS	2 Degrees	2050	Share in electricity	%	8	7	4.142857	HI
Total CCS	2 Degrees	2050	Share in electricity	%	29	7	3.428571	OK

Chapter 5

Exploring the implications of lifestyle changes in 2°C mitigation scenarios using the IMAGE integrated assessment model

Published article: *van Sluisveld M.A.E., Herreras Martínez, S.D., Daioglou, V., van Vuuren, D.P., (2015) "Exploring the implications of lifestyle changes in 2°C mitigation scenarios using the IMAGE integrated assessment model", 104, 309-319, Technological Forecasting and Social Change*

Abstract

Most model studies focus on technical solutions in order to meet the 2°C climate target, such as renewable, carbon capture and energy efficiency technologies. Such studies show that it becomes increasingly more difficult to attain the 2°C target with carbon price driven technical solutions alone. This indicates the need to focus more on non-economic and non-technological drivers of energy system transformations, which are generally not explicitly included in long-term scenario studies. This study implements a set of lifestyle change measures for residential energy use, mobility and waste management in the integrated assessment model IMAGE. We analyze the implications of these lifestyle changes in a business-as-usual and 2°C climate mitigation reference case. We find that lifestyle change measures included in this study mostly affect the end-use sectors. By 2050, the measures reduce CO_2 emissions in the residential sector by about 13% and in the transport sector by about 35% compared to baseline emissions. The indirect implications in the industry and energy supply sectors were found to be negligible. In mitigation scenarios the contribution of lifestyle measures is dampened in end-use sectors as they overlap with more technical measures. Yet, as they may create opportunities to mitigate in sectors without more radical changes (1) in the energy infrastructure and (2) on the short term, it leads to a more cost-efficient mitigation strategy. Further research in how behaviour can be internalized into integrated assessment studies is recommendable.

Keywords: Lifestyle change; behavioural change; integrated assessment modelling; 2 deg; mitigation

5.1 Introduction

Scenario analysis shows that substantial emission reductions are required in order to limit global temperature increases to 2°C. Most model studies introduce very ambitious changes in energy demand, supply and land use to meet a 2°C climate target. Common policy recommendations include, for example, large-scale introduction of intermittent renewable power, negative emissions from bioenergy with carbon capture and storage (BECCS), the introduction of advanced technologies for energy efficiency and energy supply and increased material efficiency. Generally such model studies suggest that, under full participation of sectors and regions in climate policy, it is possible to implement these energy system transformations. In reality, however, implementation of climate policy will be limited by various barriers such as economic (e.g. vested interests and sunk investments), social (e.g. values and lifestyles, cognitive routines, alignment between social groups) and political factors (e.g. opposition to change from vested interests, uneven playing field) (Cagno et al., 2013; Geels, 2005; Hof et al., 2013; Staub-Kaminski et al., 2014). In the past, this has often led to a reformulation of policy ambitions. One example of this is the European Unions' Energy Efficiency Directive, which was amended in response to the lag in achieving its primary energy consumption reduction target of 20% by 2020 (EEA, 2013).

As a result, modelling studies have started to explore non-optimal situations (e.g. limitations in joint international commitments, instrumentation and availability of technologies) (Clarke et al., 2009; IEA, 2012; Rao et al., 2008; Stocker, 2013; Tol, 2009; van Vuuren et al., 2012). These studies show that in the case of delayed action or limited technology availability the 2°C target could be unattainable.

Although assessment reports mention the notion of lifestyle change as an alternative way to reduce carbon emissions (Fisher et al., 2007; IPCC, 2014), very few studies have evaluated its potential or implications in global assessment modelling (Bernstein et al., 2007; Metz et al., 2007; Roy, 2012; Weber and Perrels, 2000). This means that while cost-optimal model scenarios are considered to be too optimistic in terms of timing of action, or technology availability, they might also be regarded as too conservative by leaving out a particular set of mitigation options. In that context, we assess alternative mitigation options by focusing on behavioural and lifestyle changes. The strength of global assessment modelling (also known as Integrated Assessment Modeling, IAM), compared to earlier studies emphasizing the contribution of lifestyle change, is that it allows to analyse the interactions of lifestyle changes with other, technical, measures.

Thus, the aim of this study is to explore the implications of lifestyle change in an Integrated Assessment Model (IAM)-based mitigation scenario and to highlight the strengths and limitations of energy demand modelling. An integrated assessment approach allows for the quantitative assessment of system impacts and the interaction between subsystems. In this respect we contribute to the aim by exploring the following research questions:

- How can lifestyle and lifestyle change be included in an integrated assessment model?
- How much could a set of lifestyle changes contribute to achieving 2°C climate targets, given the interaction with other measures?

In Section 5.2 we will address the research boundaries and introduce a framework of lifestyle change measures. Section 5.3 discusses scenario results, followed by contextual limitations in Section 5.4. Section 5.5 presents the overall conclusions of the study.

5.2 Methods and materials

5.2.1 Modelling framework

In order to explore the potential and implications of behavioural and lifestyle change, we apply the Integrated Model to Assess the Global Environment (IMAGE) modelling framework (Stehfest et al., 2014). The IMAGE framework is an integrated assessment tool that is applied to study long term dynamics of global change in the energy and land system. The framework consists of various system-dynamic sub-models, such as, among others, the energy model TIMER (Section 4.1 in Stehfest et al., 2014), coupled to the climate policy model FAIR(SiMCaP) (Section 8.1 in Stehfest et al., 2014) and the land use model IMAGE (Stehfest et al., 2014):

- Within the energy model TIMER, the annual demand and supply of different energy carriers is described for a set of 26 world regions. Changes in energy demand within the available sectors (industry, transport, residential, services, non-energy and other) are related to structural changes, autonomous and price-induced changes in energy intensity and price-based fuel substitution. Several sub-modules of TIMER simulate the various demand sectors in more detail, such as TRAVEL for passenger travel (Girod et al., 2013), REMG for household energy use (Daioglou et al., 2012) and NEDE for the non-energy (petrochemical) sector (Daioglou et al., 2013). The market share of energy carrier or technology use is determined by a multinomial logit (MNL) function, accounting for differences in relative costs and preferences per option (Van Vuuren et al., 2011).
- The FAIR model calculates the difference between baseline and global emission pathways using a cost-optimal approach involving regional marginal abatement cost (MAC) curves and combined with the SiMCaP pathfinder module uses an

iterative procedure to find multi-gas emission pathways that correspond to a predefined climate target (Van Vuuren et al., 2007b).

- The land use model of IMAGE represents the use of land for food, timber and fuel productions in relation to alternative uses of land for natural ecosystems. The area that is required could be influenced on the one hand by changes in demand and on the other by different production systems (yields).

5.2.2 Lifestyle-change measures in integrated assessment modelling

Changes in lifestyle can be expressed in changes in energy demand either through more (1) physical efficiency boosting actions or (2) curtailment measures (Gardner and Stern, 2008; Gutowski et al., 2008; von Borgstede et al., 2013). In this study we zoom in on curtailment measures as people are found to be more likely to carry out environmentally friendly behavioural changes with low cost and low efforts than others (Steg, 2008). Moreover as energy efficiency improvement measures overlap with technological improvements already included in the model, we exclude these measures here.

Global Integrated Assessment Models (IAMs) generally do not explicitly model individual decision making. Instead, various proxies are employed to internalize some degree of behavioural variation. In the IMAGE framework the following elements represent some of the decision-making processes:

- Many decisions in the model are represented by (multinomial) logit functions that assign large market shares to attractive (low costs for the service) options and small or no market share to unattractive (expensive) options. This equation embeds decisive heterogeneity in the model. The market shares are determined by logit parameters simulating price sensitivity, hence imposing a certain price-elastic preference order.
- Related to the previous bullet, in evaluating the attractiveness of different options the multinomial logit equations not only include energy prices but also other factors representing consumer preferences or governmental policies in so-called 'preference' or 'premium' factors (De Vries et al., 2001). Preference factors seek to represent a wide variety of empirically unquantifiable (market) externalities;
- Regional diversity is accounted for through calibrating on differences in energy demand per region, e.g. refrigeration energy use is explicitly different in the USA than for other regions, whereas floor space per capita is significant lower in Japan (Daioglou et al., 2012);
- In some cases constants are applied that represent a certain exogenous trend within the model (e.g. fixed vehicle occupancy rates, discount rates, lifetimes).

There are several ways to analyse the impact of behavioural change in the model. As explained further, we look at a set of identified lifestyle change measures. The impact of these measures can be included in IMAGE by changing the existing parameterisation. This includes:

(1) Adjusting the (multinomial) logit parameters to change the preference order for specific choices (e.g. transport mode);
(2) Allowing regional energy demand parameters to converge to a top performing region;
(3) Capping parameters to a certain value (e.g. ownership rates can be fixed to (or abolished from) current day ownership rates).

5.2.3 Framework of lifestyle change measures

For the purpose of energy demand modelling we consider lifestyle change as an activity that is manifested in the housing and transport domains, including end-of-life considerations (Bedford et al., 2004; Daioglou et al., 2012; Girod et al., 2013; OECD, 2008). Below we describe the lifestyle change measures that have been selected from literature and how these are translated into the IMAGE model framework.

5.2.3.1 Household domain

In the household domain, lifestyle measures can be identified with respect to space heating, water heating, appliance use and waste management.

Space heating

- <u>Reducing demand for cooling and heating</u>

The most common climatic indicator of the demand for heating and cooling services is the degree day (in °C/yr). The degree day describes the number of degrees above or below a certain desired temperature over an entire year (which may vary for heating and for cooling) (Isaac and van Vuuren, 2009). We assume a behavioural change in which a user accepts a difference to the desired (room) temperature by adapting the base temperature of 18 degrees by 1°C downwards (for space heating) or 1°C upwards (for space cooling).

- <u>Capping household dimensions</u>

For most developed countries, larger dwelling sizes (0.7% increase in energy demand per annum) and lower occupancy rates (0.5% increase in energy demand per annum) have tended to drive up energy demand for space heating, offsetting reductions achieved through efficiency gains (IEA, 2008). Hence, limiting home size has been suggested as a measure in literature (Dietz et al., 2009). To approach this lifestyle change, we assume that with increasing affluence, the increase of floor space per capita is limited to 2010 levels of a representative developed region (EU). This scenario also explicitly differentiates between urban and rural regions, of which the values are set at 40 m^2/cap for urban households and 50 m^2/cap for rural households (allowing regions with greater values to converge within a decade) (IEA, 2004). The measure can also be seen as a limitation to the heated and/or air conditioned surface area in homes.

Water heating

- Reduced use of heated water

Heating water uses about a third of the annual gas used for space heating in high-income areas (Goodall, 2010), and is mainly done for activities such as, among others, showering and cleaning. With an assumed average of 8 minutes a day to shower, we assume a reduction of shower time of 2 minutes to reduce the energy needed for heating water. We apply a correction factor in total energy demand for water heating based on an estimate calculated from literature. With an estimated water throughput of 15 L/min (Wright, 2011), a required temperature elevation of 50°C, and a 0.0011 kWh/L energy consumption per degree of water heating (Goodall, 2010), on average, this could lead to a 25% energy reduction.

Appliance use

- Reduced rate of appliance ownership per household

In developed regions, large appliances such as refrigerators, freezers, washing machines, dishwashers and televisions account for about 50% of household electricity consumption in appliances (IEA, 2008). An important driver of appliance energy use is the rate of ownership. We limit maximum ownership rates for major domestic appliances and entertainment devices to the present maximum ownership rates, which would have increased over time otherwise. For tumble dryers we assume they are gradually phased out over the decade.

- Switch off standby mode

Between 3% and 13% of residential electricity use in high-income regions can be attributed to standby power consumption (de Almeida et al., 2011; EEA, 2005). Specifically office equipment (such as information and communication technologies) and entertainment devices (such as consumer appliances) have the largest share in standby energy demand (de Almeida et al., 2011). We assume an appliance standby energy use as listed in LBNL (Lawrence Berkeley National Laboratory, 2013), and deduct this from the total average energy consumption per appliance category as described in Daioglou et al. (2012).

- More efficient or smarter use of appliances

A number of energy-conscious behaviour options can be considered for appliances, such as choosing different wash temperatures, maximizing washing load per cycle, switching off the oven or the hotplates before the end of a cooking period, locating 'cold' appliances wisely (e.g. not near an oven), cooling hot food before storing or thawing food in the refrigerator and keeping it filled up (or limit the use of 'over-dimensioned' appliances) (Geppert and Stamminger, 2010; Lucon et al., 2014; Wood and Newborough, 2003). Due to varying reduction potentials in the various measures (see for an overview Geppert & Stamminger 2010; Lucon et al. 2014), we assume the best available technology (BAT) energy consumption for technology functions as a proxy for possible reduced energy demand per appliance category (Goodall, 2010; Lawrence Berkeley National Laboratory, 2013).

Waste management

- Reduced demand for consumer plastic

Waste management is expected to be an increasing challenge, as the generation of municipal waste is projected to increase within the OECD regions (OECD, 2008). Reusing plastic bags or using durable plastic products rather than disposables could reduce the total volume of municipal waste. This measure is implemented by reducing the intensity of useful energy demand in the industry and non-energy sectors to represent reduced material processing. We reduce the energy intensity of demand for the ethylene sector with 15-20% to depict reduced energy demand for plastics production. This in turn reduces the demand of primary energy to be used as feedstock, but also process energy in the form of heat and electricity.

- Plastic waste recycling

In order to assess possibilities of material efficiency improvement throughout the lifecycle of non-energy products (such as recycling and incineration with electricity generation), we also account for possible routes of post-consumer plastic waste (PCW). It is assumed that 50% of plastic production can be collected as PCW and recycled. The volume of PCW undergoing mechanical recycling is capped at 30% in order to account for decreased material properties (down-cycling), the remaining PCW undergoes chemical recycling processes.

5.2.3.2 Transport domain

In the transport domain, there are various lifestyle measures related to curtailment. Here, we discuss reduced vehicle use and a mode shift to public transport.

- Reduced vehicle use

As described in Schäfer and Victor (2000) and Schäfer et al. (2009), individuals reserve a fixed proportion of income for traveling (travel money budget, TMB), which increases with economic growth and analogous rising motorization rate (number of light duty vehicles per 1000 inhabitants).The TMB increases till saturation is reached at 10-15% in (high-income) motorized regions, as opposed to 3-5% in non-motorized (developing) regions. In order to dampen the increase of motorization (e.g. representing car sharing or carpooling), we cap the TMB to the reported value for Japan (7%) which is the lowest reported value in literature for a developed region[4]. We allow the model to adjust to this value over an interval of a decade. Moreover, to slow down the decrease in vehicle occupancy with rising income, we introduce an income elasticity of -5% for all transport modes (Girod et al., 2013).

- Mode shift to public transport

Despite limiting the available TMB, the continuous increase of income leads simultaneously to a higher preference for faster modes. To reduce high-impact traveling we influence the mode split by differentiating non-monetary preferences per mode, in favour of the bicycle and railway transportation, similarly to Girod et al. (2013). Moreover, to correspond with the increase in the preference for slower modes, we allow an additional 0.5 minute per year on the traveling time budget (TTB).

Table 5-1 summarizes the measures that have been implemented in the IMAGE model framework. The introduced lifestyle changes include actual or estimated changes in energy demand as reported in literature. As some measures are only qualitative prescriptions (e.g. downsizing your home) we translate these into the model by using historical and regional best practices already included in the model. We also distinguish between measures that can take immediate effect and those that require an adjustment from the current situation.

5.2.4 Scenario design

For this study we introduce four different scenarios to analyse the implications of lifestyle change in a 2°C scenario and an integrated assessment context (see Table 5-2).

1) The baseline scenario (*Baseline*) is a stylized scenario assuming business-as-usual without detailed assumptions on planned (regional) climate policy. Projections for GDP growth rates stem from the OECD Environmental Outlook (OECD, 2010b) which describes an average annual global growth rate of 3.5% between 2010 and 2050. Population assumptions are based on the United Nations population prospects (UN, 2008), in which the global population reaches 9.55 billion at the end of the century. For this baseline, the IMAGE projections on energy consumption are similar to the projections of the IEA World Energy Outlook (IEA, 2011) showing a continuation of historical trends and the range found in literature as reviewed by van Vuuren et al. (2012).
2) A second scenario (*Baseline + lifestyle*) combines the baseline projection together with the lifestyle change measures as described in the framework, to assess the contribution of lifestyle change relative to the default settings.

4 Driven by an exceptional large share of public high-speed transport in Japan, due to e.g. the *Shinkansen* high-speed rail way (Schafer and Victor, 2000).

Table 5-1: Overview table of implementable changes in lifestyle and the energy reduction potential considered.

Domain	Measure	Implementation	Transition	Source
Transport	**Reduced vehicle use**	• *Capping the travel money budget.*	*Gradual*	*TIMER/IMAGE* (Girod et al., 2013)
		• *Changing income elasticity to -5% to prevent lower passenger load per mode*	*Immediate*	
	Mode shift to public transport	• *Change of perceived price and increase of TTB by 0.5 min/yr*	*Immediate*	*TIMER/IMAGE* (Girod et al., 2013)
Household	**Reduced heating / cooling demand**	• *Change of base temperature by 1 degree, reducing the number of heating degree days or cooling degree days.*	*Immediate*	*TIMER/IMAGE* (Isaac and van Vuuren, 2009)
	Reduced appliance ownership	• *Reduced ownership levels for 'luxury goods' to zero (no tumble dryers, dish washers etc.*	*Gradual*	*TIMER/IMAGE*
		• *Maximum ownership rates for other major domestic appliances are fixed to 2013 values.*	*Immediate*	
	More efficient use of appliances	• *BAT energy consumption estimates and make appliances converge to these new levels gradually over time.*	*Immediate*	(Goodall, 2010)
	Switch off stand-by mode	• *Reduce annual appliance energy consumption based on estimations of standby mode energy consumption per appliance*	*Immediate*	(Lawrence Berkeley National Laboratory, 2013)
	Reduces water heating	• *A correction factor in total energy demand for water heating (based on cutting down 2 min of shower time), based on an estimate in literature.*	*Immediate*	(Goodall, 2010) (Daioglou et al., 2012)
	Capping household dimensions	• *Maximum floor space (m^2/cap) is fixed to a representative 2010 value, differentiating for rural (50m^2/cap) and urban households (40 m^2/cap)*	*Immediate*	*TIMER/IMAGE* (IEA, 2004)
	Reduced plastic consumption	• *Reduce intensity of useful energy demand in ethylene production by 15-20%*	*Gradual*	*TIMER/IMAGE*
	Plastic waste recycling	• *Assuming active household plastic waste separation from general waste.*	*Immediate*	TIMER/IMAGE (Daioglou et al., 2013)
		• *Assuming available infrastructure in which max. 20% is mechanically recycled and max 30% chemically recycled.*	*Immediate*	

Table 5-2 - Scenario overview table

Scenario	Subname	Description
Baseline (default)	-	The baseline scenario used throughout this study.
Baseline + lifestyle	-	The baseline including all the lifestyle measures addressed in the lifestyle change framework.
2 Degrees (default)	-	A cost-optimal mitigation scenario with primarily price-based mitigation measures that stay in line with a 450 ppm climate stabilization target in 2100.
2 Degrees + lifestyle	ctax	A mitigation scenario that includes lifestyle change measures next to price-based mitigation measures.
	ppm	A cost-optimal mitigation scenario allowing lifestyle change measures to exist in tandem with price-based mitigation measures.

3) The third scenario (*2 Degrees*) consists of a default, cost-optimal mitigation scenario as calculated by the model targeted to not exceed the 2°C temperature increase, assuming no lifestyle changes.
4) Finally, the fourth scenario (*2 Degrees + lifestyle*) combines the same lifestyle assumptions as considered under the *Baseline + lifestyle* scenario with a climate mitigation target. This scenario can be interpreted in two ways:
   a) The first way is to introduce lifestyle change measures as additional to the existing cost-optimal mitigation scenario. The outcomes reflect the additional mitigation potential that can be achieved via lifestyle change next to an existing set of more large-scale infrastructure and technology-oriented measures. This translates into the model as a similar carbon tax (ctax) price path over time as in the default *2 Degrees* scenario.
   b) The second way is by allowing lifestyle change measures to exist in tandem with carbon price driven measures – in this situation a new cost-optimal optimum reflects the implications of lifestyle change on the required mitigation efforts. In the model this translates into a scenario meeting a similar concentration target (ppm) in 2100 as the default *2 Degrees* scenario.

   To assess the implications of lifestyle change and to control for the various system interactions we mainly address the first interpretation in the forthcoming results.

This study focuses on the aggregated (global) level, with a temporal scale up to 2100 and zooms in onto four sectors (energy supply, industry, residential and transport). The energy supply sector accounts for power and heat generation and other energy conversions (e.g. refineries, synfuel production), resource extraction and energy transmission and distribution (e.g. gas pipelines). The industry sector includes heavy industry such as steal and cement production and petrochemicals. The residential and commercial sector includes both heating and cooling as well as appliance energy use. The transport sector includes freight and passenger travel and bunker fuels.

To assess the implications of lifestyle change measures on attaining the 2°C objective the analysis focuses on CO_2 emission trajectories and secondary energy carriers. Amongst the energy carriers addressed, solid fuel denotes coal (incl. cokes and other commercial solid fuels), liquid fuel denotes oil as light liquid fuel (LLF) or heavy liquid fuel (HLF) and commercial liquid fuel from biomass, gaseous fuel denotes natural gas.

5.3 Results

5.3.1 Direct implications of lifestyle change

In the following paragraphs we will discuss the implications of lifestyle change for each sector.

5.3.1.1 Residential

The residential and commercial sector has been responsible for about 32% of total global final energy use and 19% of energy-related greenhouse gas emissions in 2010 and is expected to double or triple its emissions by mid-century due to increasing life-standards in emerging regions. The largest part of greenhouse gas emissions are indirect CO_2 emissions from electricity use in buildings (Lucon et al., 2014), followed by emissions from direct energy use (with space heating and water heating as most energy consuming respectively) (Steg, 2006).

In the baseline scenario, emissions in the residential and commercial sector are projected to increase from less than 3 $GtCO_2$ today to 4 $GtCO_2$ by 2100 (See Figure 5-1). We find that the set of lifestyle change measures can lead to a sustained emission reduction potential of about 13% over time (and as early as 2030, see Table 5-3). Under stringent 2°C climate ambitions, the calculations show that the measures have become less effective if combined with technology and energy efficiency (showing even a decreasing additional effect over time).

Table 5-3 - overview of emission reductions compared to baseline emissions for household related lifestyle change measures in the IMAGE model (in %)

	Reductions compared to *Baseline*		
	2030	2050	2100
Baseline + Lifestyle	13%	16%	15%
2 Degrees	24%	50%	84%
2 Degrees + Lifestyle (ctax)	34%	58%	87%

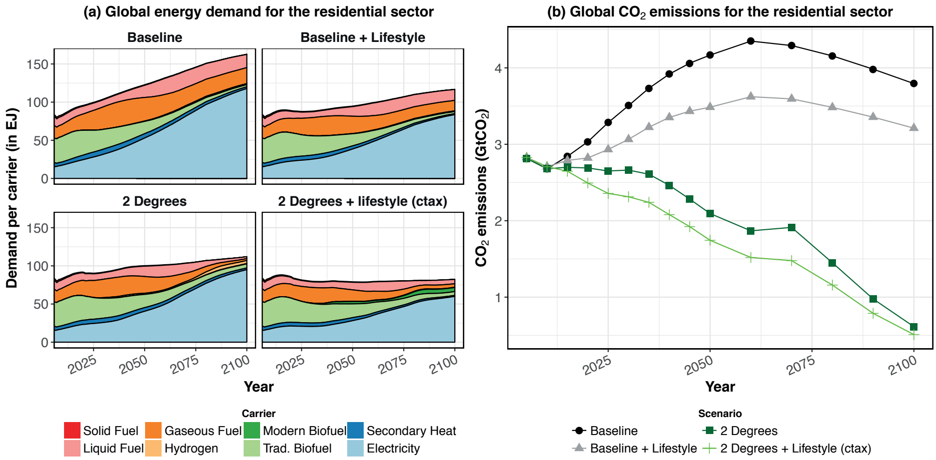


Figure 5-1 - Overview of the effect of lifestyle changes in the residential sector on the use of secondary energy carriers (panel a, in EJ) and CO_2 emission trajectories (panel b, in $GtCO_2$).

5.3.1.2 Transport

The transport sector is often considered to be the most difficult and expensive sector to reduce greenhouse gas emissions (Schäfer and Victor, 2000). Conventional mitigation strategies focus on supply-side vehicle technology efficiency gains and fuel switching as the central theme for this sector. These measures create several challenges on the short term as most aspired technological changes are not yet commercially available and require major infrastructure changes and investments (Anable et al., 2012).

Lifestyle changes on the other hand could lead to an immediate shift from a predominant oil and bioenergy orientated to a more electrified transport sector (see Figure 5-2). This is an effect of the mode shift from personal vehicles to public transport, which opens up opportunities to use renewable energy sources on the short term without substantial changes to the energy infrastructure. This change in transportation behaviour has the potential to achieve an increasing emission reduction potential in the transport sector over time (see table 5-4), with a sustained reduction potential of about 35% by 2050 compared to baseline emissions. However, similar to the residential sector, we find that under 2°C ambitions the lifestyle change measures lead to a relatively smaller reduction potential than the reduction potential achieved under *Baseline* assumptions (creating only a 7 to 13 percentage point deviation from the default over time).

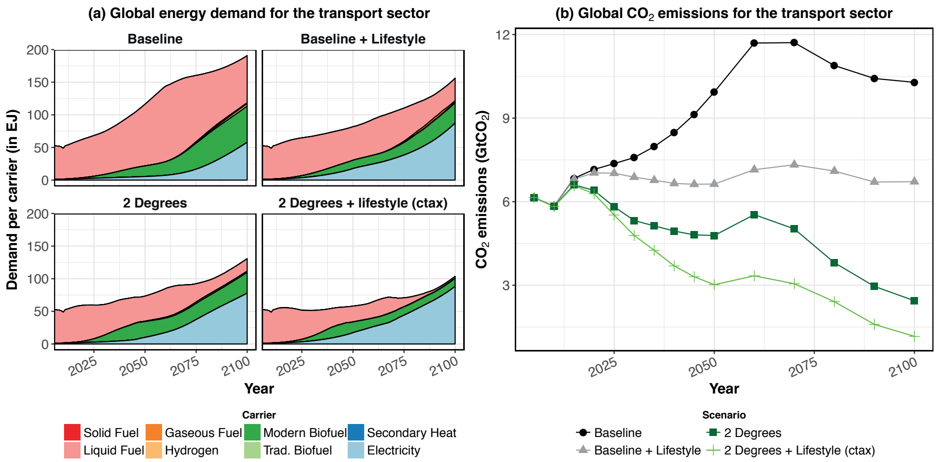


Figure 5-2 - Overview of the effect of lifestyle changes in the transport sector on the use of secondary energy carriers (panel a – limited to passenger travel in EJ) and CO_2 emission trajectories (panel b, in $GtCO_2$).

Table 5-4 - overview of emission reductions compared to baseline emissions for the transport related lifestyle change measures in the IMAGE model (in %)

	Reductions compared to *Baseline*		
	2030	**2050**	**2100**
Baseline + Lifestyle	9%	33%	35%
2 Degrees	30%	52%	76%
2 Degrees + Lifestyle (ctax)	37%	70%	89%

5.3.2 Indirect implications of lifestyle change

Although lifestyle measures are not implemented in the energy supply and industry sector directly, some of the measures regarding energy and material conservation will lead indirectly to impacts in these sectors.

5.3.2.1 Power sector

The energy supply sector is acknowledged to be the largest contributor to global anthropogenic greenhouse gas emissions, responsible for 35% in 2010. Although multiple options exist to reduce energy supply sector greenhouse gas emissions, the central theme in long-term mitigation scenarios is generally the development and deployment of low-carbon technologies (Clarke et al., 2014). Society can have an indirect impact on the power supply sector and the composition of fuel for power generation by changing their energy consumption – either through reducing energy demand or by increasing the use of electricity in the household and transport domain. We observe that the introduced lifestyle changes lead to changes in electricity demand

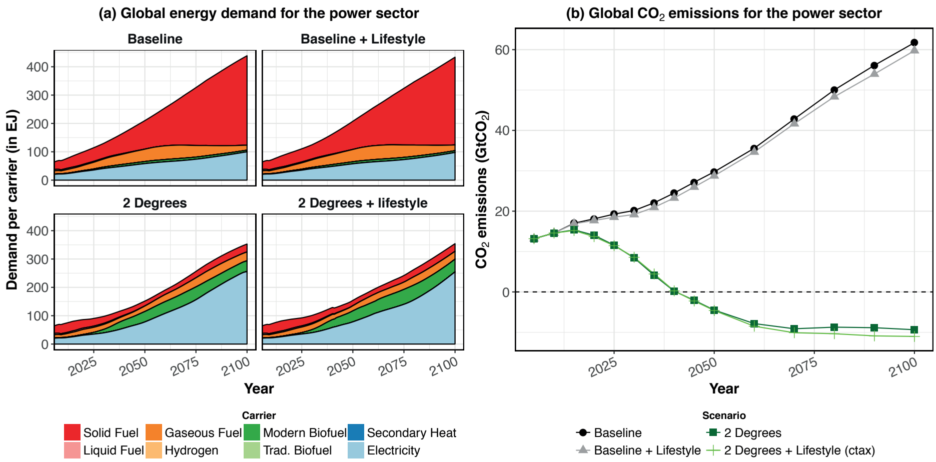


Figure 5-3 - Overview of the effect of lifestyle changes on the power sector on the use of secondary energy carriers (panel a - in EJ, 'Electricity' represents power generated by renewable sources) and emission trajectories (panel b, in $GtCO_2$).

in the residential and transport sector, but these do not have a significant impact on the fuel mix or emissions in the power sector (see Figure 5-3). Overall a sustained emission reduction potential of about 3-5% is achieved by 2030. In a 2°C context an additional 2 percentage point greater emission reduction potential can be achieved in the energy supply sector compared to the default 2°C mitigation scenario.

5.3.2.2 Industry

Despite continued improvements in energy and process efficiency, industry related emissions are increasing and represent just over 30% of global greenhouse gas emissions in 2010 (Lucon et al., 2014). Lifestyle change measures can indirectly impact the producing industry through reducing material consumption (e.g. through curtailment and recycling and re-use). The effects of lifestyle change measures on the industry sector show to be limited in both the baseline as well as the *2 Degree* scenario. This is partly an effect created by only implementing measures that explicitly target the petrochemical sector (such as plastic reuse and recycling), as well as an effect of limited feedback of the industry to other demand sectors and vice versa. Hence in this study we find that a lower demand for materials (mainly polymers) leads to emission reductions that have a near negligible effect in the total industry sector (increasing up to 4% by 2100) (see Figure 5-4). Indirect effects of lifestyle changes in the transport sector and residential and commercial sectors are not further included in this estimate.

Overall, as underlined in the results, lifestyle changes do not impose large structural changes in the energy intensive sectors under both *Baseline* as *2 Degrees* assumptions.

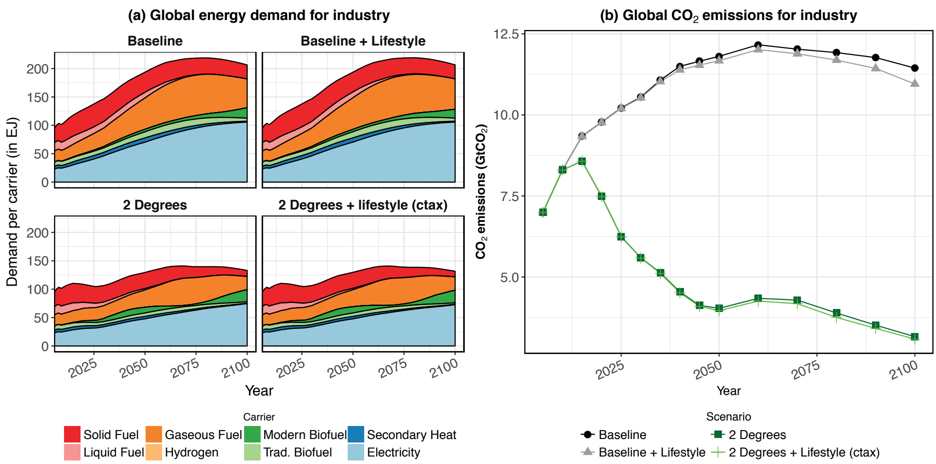


Figure 5-4 - Overview of the effect of lifestyle measures in the industry sector on the use of secondary energy carriers (panel a) and emission trajectories (panel b, in $GtCO_2$).

This implies that in order to decarbonize these sectors the mitigation efforts remain dependent on technology-oriented measures. Given how the added effect of lifestyle change measures become relatively smaller under *2 Degrees* assumptions, we deduct that this is an effect of a decarbonizing energy system. However, as society is decarbonizing its energy intensive sectors, the weight of meeting 2°C ambitions will shift to sectors that are less easily decarbonized. Especially for those sectors, lifestyle changes will play a vital role in reducing carbon emissions more early on (like the transport sector).

5.3.3 Implications of lifestyle change on 2°C mitigation

Limiting temperature increase by 2°C with a high likelihood (>66%) is often linked with staying within a cumulative CO_2 emission budget of 1000 $GtCO_2$ over the 2011-2100 timeframe (Clarke et al., 2014). Under *Baseline* assumptions the cumulative emissions reach up to 5000 $GtCO_2$ in 2100. Lifestyle change measures show to have only a limited impact on the system as a whole - depicting a reduction potential of about 7% in total cumulative CO_2 emissions by 2100. Lifestyle change measures alone thus prove to be insufficient to stay in line with 2°C ambitions (see Figure 5-5).

Initially the impact of lifestyle change measures in a mitigation scenario on total CO_2 emissions appear to be analogous to the *Baseline*-equivalent. However, several vital differences can be observed. First of all, in order to not exceed the 1000 $GtCO_2$ carbon budget the energy system has to transform to a carbon neutral system which can be achieved no sooner than 2090 under cost-optimal assumptions. However, low effort

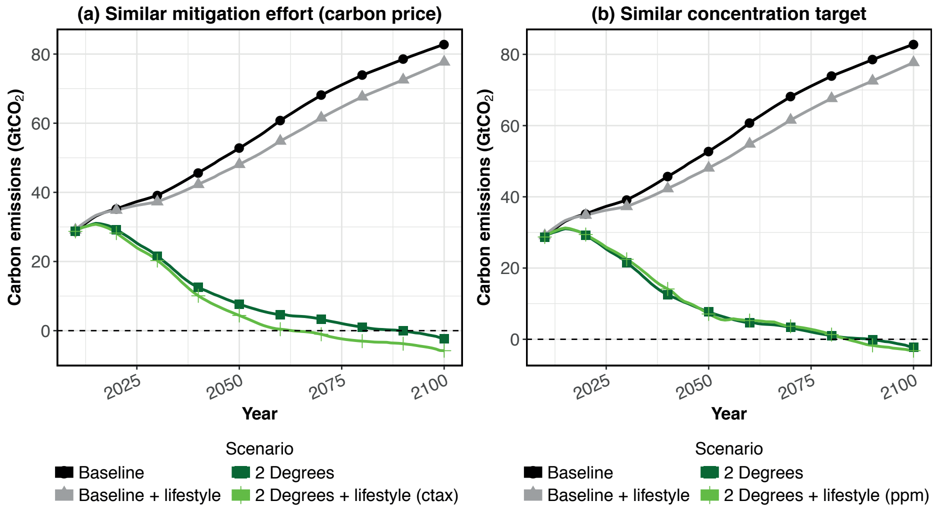


Figure 5-5 - CO_2 emission trajectories for similar carbon pricing (panel a, in $GtCO_2$) and similar climate target (panel b, in $GtCO_2$).

and low cost lifestyle changes create additional emission reductions throughout the century leading to a total carbon budget of about 650 $GtCO_2$ in 2100 (or 27% less cumulative emissions than under default *2 Degrees*). This is an effect of achieving negative emissions already by 2060.

If we correct for this effect by preventing the carbon budget to go beyond what is in line with 2°C (*2 Degree +lifestyle* (*ppm*)), we find that lifestyle change measures allow a greater cumulative emission profile over the first half of the century. This higher emission profile is a manifestation of reduced energy demand in society, which dampens the adoption rate of more biomass-based energy supply and carbon storage technologies to replace existing capital and to compensate for the increasing energy need on the short-term. In the second half of the century the *2 Degree + lifestyle (ppm)* scenario follows a similar route as under default 2°C settings, but due to reduced overall demand and an movement towards electric based transport, a greater volume of biomass has become available to be utilized in the power sector. This leads eventually to deeper negative emissions at the end of the century.

Overall, by pre-emptively reducing energy demand and transitioning to electricity-driven end-use sectors, multiple opportunities are unlocked to mitigate in the more difficult to mitigate sectors. This is in particular reflected in the required carbon pricing and total mitigation costs to remain within a carbon budget of 1000 $GtCO_2$. As illustrated in Figure 5-6, lifestyle change measures create a more cost-efficient mitigation scenario without additional radical changes in energy infrastructure. This is represented by a carbon price value that is USD$100/t$CO_2$ (or a sustained 15%) lower throughout the century under lifestyle assumptions compared to the reference scenario. It is however important to underline that this effect is achieved by assuming that lifestyle changes can be realized without any costs for people or policies.

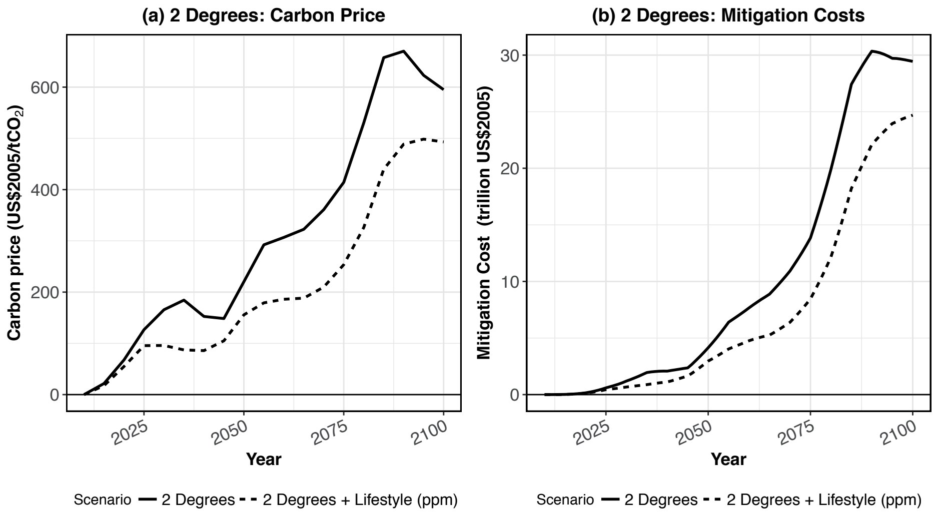


Figure 5-6 - Differences in required carbon tax projections (left, in US$2005) and total mitigation costs (right, in US$2005) for the *2 Degrees* and *2 Degrees + lifestyle scenario (ppm)*

5.4 Discussion

5.4.1 Representation of lifestyle change in IAMs

In this study we have analysed 10 different lifestyle change measures to reduce greenhouse gas emissions which are assumed to be of low cost and low effort in nature. Some caveats with respect to the analysis need to be accounted for:

1) **Methodological limitations:** The measures studied in this study are to some degree an arbitrary selection from the existing literature. Some scholars argue that focusing on low cost and low effort lifestyle measures, if unranked in terms of energy reduction potential, is not effective (Gardner and Stern, 2008). In this study we focus more on curtailment measures which have a less quantifiable energy reduction potential than efficiency measures and could in this light be considered as less significant environmental behaviour. However, as argued in Poortinga et al. (2003) people probably undertake energy saving actions that are based on more popular notions of pro-environmental behaviour (such as very simple and homy

measures) and thus the measures tested in this study can be considered of higher symbolic value. The results in this study, surprisingly, also compare to reduction potentials as reported in literature for the short term (20% in both the residential (Dietz et al., 2009; Lucon et al., 2014) and transport sector (Sims et al., 2014)). This is surprising, as these studies do not differentiate between efficiency and curtailment behaviour as explicitly as this study and also assume more radical change in the energy infrastructure.

Moreover, this study assumes changes in behaviour that can be induced without any costs for the individual or intervening policies. This is most likely not the case, particularly considering the wide variety of behavioural intervention options (which vary in their success) and their short-lived effects (Abrahamse et al., 2005). Future work could include the evaluation of the costs of policy interventions required to achieve behavioural change, specifically as cost factors appeal to integrated assessment modelling.

2) **Limited representation of lifestyle change in IAMs:** The way we have implemented most lifestyle change measures is by changing context-dependent variables. As socio-economic trends (such as low education, income, age, gender, employment status and attitudes) (OECD 2008) and the interactions with lifestyle are not dynamically captured, one might argue that the study design is characterized by highly stylized assumptions.

   An entry point to stepping away from ad-hoc implementation could be found in extending the influence of contextual factors next to the common carbon price driven responses or by creating further boundaries to optimization. Information needs to become available on the diversities and heterogeneities of behaviour (e.g. preferences, agents, geographies, influence of past experiences) and included in the model. Further research could also focus on integrating other principles from techniques that model behavioural diversities more explicitly (e.g. agent-based modelling).

3) **Limitations in integrated assessment:** Generally energy models have a stylized representation of energy and material demand, which is mostly based on historically observed correlations between economic activity, energy or material intensity and energy or product demand. Although various interrelations are included in the IMAGE model, such as the interaction between energy demand for space heating, floor space, heating degree days and heating intensity ($kJ_{UE}/m^2/HDD$) (Daioglou et al., 2012; Isaac and van Vuuren, 2009), these are generally limited to the feedbacks

between energy demand, energy resources and energy prices. The result of this is that feedbacks between various sectors are limited (i.e. impact of reduced vehicle use and reduced floor space on the automobile and cement industries is not represented). Furthermore, as behavioural diversities are based on exogenous socio-economic parameters, the effect of reduced consumption on these is also poorly represented.

It should be noted that the purpose of this study is to qualitatively assess the possible implications of lifestyle change in mitigation scenarios rather than quantifying the available potential exactly. Therefore, we consider these caveats to be not important in the light of the conclusions.

5.4.2 Barriers and policies for lifestyle change measures

Several real-life challenges also exist which limit the potential and up-take of lifestyle change. There are several factors that play a role in real-world implementation of the measures discussed in this study.

1) **Ability to adopt**: The ability to adopt certain lifestyle changes is highly dependent on contextual factors, such as the availability of knowledge, the available infrastructure, cultural norms and economic factors (Steg, 2008). As described in Csutora (2012), Gatersleben et al. (2002) and Tabi (2013), the energy demand for heating and electricity seems to some degree more closely related to socio-economic and demographic factors (e.g. income, household size, family composition) than any other factor. Willing individuals might therefore have limited space to dissociate itself from environmentally indifferent behaviour.

2) **Tailored approach:** Generally a combination of regulatory, economic and information-based instruments ("policy packages") are more effective than single policy instruments (Rohde 2012; OECD 2008; Abrahamse 2005). Although information campaigns achieve only modest changes in behaviour, they are in particular effective for low cost and low effort changes (Steg, 2008). The participation rate could be increased by combining information-based tools with regulatory policy instruments, such as obligating the collection of waste as well as capping the use of plastic per capita. The effectiveness of economic instruments is more dichotomous, as they can be push (making environmental unfavourable behaviour more expensive and subsequently less attractive) or pull incentives (making environmental behaviour less expensive). Pull measures are perceived as more voluntary (freedom of choice) and are therefore more accepted, yet may be

less effective than push measures because these are noncommittal in nature (Steg, 2008).

3) **Continuous priming:** Measures to overcome habitual behaviours are aimed at increasing the level of awareness, which require tailored and repeated knowledge until the desired change is acquired or in line with current (energy saving) trends. Maintaining these changes in behaviour is specifically challenging, as is illustrated in a plethora of behavioural phenomena that describe the return to habitual behaviour (such as the drawback effect (EEA, 2013) or various change undermining behaviours (such as observed with the so-called rebound effect (Madlener and Alcott, 2009), boomerang effect (Harding and Rapson, 2013)) or moral licensing (Tiefenbeck et al., 2013))

4) **Extent:** As people are more familiar with ways to reduce direct energy use than indirect energy use, incentives to reduce energy demand in households are perceived as more favourable. Direct energy use has the benefit of being more easily monitored on meters in and around the house, whereas for indirect energy use it is unclear how far the extent reaches (Steg, 2008). This in particular creates obstacles in implementing lifestyle changes in, for example, sustainable consumption for which also substantial reduction potential is reported (in particular for reduced meat consumption) (Stehfest et al., 2009).

Introducing and sustaining lifestyle change is thus not as straight-forward as a (prescriptive) modelling approach may suggest. The design of a successful policy strategy requires knowledge of all these factors that determine and sustain changes in specific behaviours.

5.5 Conclusion

This study aimed to explore the implications of various low-cost and directly implementable lifestyle changes in a 2°C mitigation context. By using the IMAGE integrated assessment framework we have compared four scenarios in terms of secondary energy demand, carbon emission reductions and their economic potential to their reference case. The main conclusions on this study are:

This study presents a relatively simple method for assessing lifestyle changes measures in IMAGE. Integrated assessment models generally do not explicitly model behaviour. Within the IMAGE framework behavioural heterogeneity can be embedded through mechanisms causing a specific order of preference based on (non-) energy prices and by capping or fixing other energy demand drivers. In this study we introduced lifestyle measures by changing key model parameters in line with estimates in literature. This method provides a relatively simple method to assess the implications of lifestyle change measures in an integrated assessment context. However, as socio-economic trends and various interactions between sectors are not dynamically captured in the model, study designs like these are characterized by highly stylized assumptions. In order to conduct more proper behaviourally-realistic modelling, information needs to become available on the diversities and heterogeneities of behaviour (e.g. preferences, agents, geographies, influence of past experiences) and included in the model.

Lifestyle changes are most effective in the end-use sectors, leading to a CO_2 emission reduction potential of about 15% in the residential and 35% in the transport sector compared to baseline emissions. The results show that lifestyle change can impact fuel demand and carbon emissions both directly and indirectly in the residential sector, mainly through changing (water) heating habits and by reducing appliance energy use. These lifestyle changes can lead to a reduction of residential emissions by about 13% compared to the baseline assumptions. Furthermore, structural changes in travel behaviour could reduce CO_2 emissions in the transport sector by about 35% in 2050 compared to baseline emissions. In the power sector, as well as the industry sector, lifestyle changes generally have an indirect impact– leading to negligible changes in fuel composition and emission reductions.

The effects of lifestyle change measures in mitigation scenarios are analogous to baseline scenarios but the overall impact is reduced. The lifestyle change measures considered in this study are on their own insufficient to meet the 2°C climate objective. Moreover, as these changes do not impose large structural changes in the energy intensive sectors under both *Baseline* as *2 Degrees* assumptions, a 2°C mitigation strategy remains dependent on technology-oriented policy measures. However, in mitigation scenarios, the contribution of lifestyle measures are dampened in the end-use sectors as the effectiveness overlaps with more technology-oriented measures.

Lifestyle change measures create opportunities to mitigate in sectors without more radical changes (1) in the energy infrastructure and (2) on the short term. This leads to a more cost-efficient mitigation strategy. By pre-emptively reducing energy demand and transitioning to electricity-driven end-use sectors, multiple opportunities are unlocked to mitigate in the more difficult to mitigate sectors. Moreover, it allows for a more gradual energy transition as lifestyle changes allow for a greater cumulative emission profile over the first half of the century. This is in particular reflected in the required carbon pricing that is USD\$100/tCO_2 (or a sustained 15%) lower throughout the century under lifestyle assumptions compared to the reference.

Acknowledgements

The research leading to these results has received funding from the European Union Seventh Framework Programme FP7/2007-2013 under grant agreement n°282846 (LIMITS) and n°603942 (PATHWAYS). The authors would like to thank Bastien Girod at ETH Zürich for providing comments and suggestions that helped to improve this article.

5

Chapter 6

Aligning Integrated Assessment Modelling with Socio-Technical Transition insights: an application to low-carbon energy scenario analysis in Europe

Submitted: *van Sluisveld, M.A.E., Hof, A.F., van Vuuren, D.P., Carrara, S., Geels, F., Nilsson, M., Rogge, K., Turnheim, B. (submitted) "Aligning Integrated Assessment Modelling with Socio-Technical Transition insights: an application to low-carbon energy scenario analysis in Europe"*

Abstract

In this study we present and apply an interdisciplinary approach that systematically draws insights from socio-technical transition studies to develop new scenarios for integrated assessment modelling. We use the concept of transition narratives as an operational link, which allows to distinguish between two fundamentally different transition pathways with respect to the role of actors, the role of governance and the kind of technologies being considered. In one pathway, large-scale innovation trajectories are driven by incumbent actors, whereas the second pathway assumes a more 'alternative options' discourse, enacted by new entrants with strong opposition to large-scale (controversial) technologies. Based on multiple multi-level perspective studies, a typology has been created that frames the current momentum of various niche-innovations and the type of actor driving the prospective transition. To assess the impact of more realistic assumptions on future systems change within model-based analysis, the typology and the information provided in the multi-level perspective studies allowed for a more mixed implementation of expected breakthrough potential for a wide variety of niche-innovations in an integrated assessment model (TIMER/IMAGE). The study specifically looked into the changed course of development in the light of meeting the European Unions' 80% greenhouse gas emission reduction objective for 2050. The results illustrate how two fundamentally different transitions pathways, which are characterised as either focusing more on technological substitution or broader regime change solutions, can lead to meeting the long-term climate objective. Each transition narrative scenario, however, depicts substantial departure from systems that are known to date. Future research could focus on further systematic (joint) development of operational links between the two analytical approaches, as well as work on improved representation of demand-oriented solutions in techno-economic modelling.

Keywords

Interdisciplinary, MLP, integrated assessment, IAM, socio-technical transitions

6.1 Introduction

Transitions towards a low-carbon society depend on a wide range of different factors, including socio-economic development, technological change, infrastructure and lifestyle preferences, but also institutional factors and the interests of various actors. Integrated Assessment Models (IAMs) are often used instruments to analytically support our understanding of transitions, global climate change and the various complex interlinkages between human and natural subsystems. Due to their comprehensive representation of global systems, IAMs allow to evaluate the implications of different policy decisions on both the human and natural system. However, in their conceptualisation of (global) systems change, IAMs usually focus on aggregated universal processes that can be captured by mathematical formulations. This generally results in a strong focus on principles found in (energy) engineering and neo-classical economics, which may frame the presented outcome in terms of (1) cost-effectiveness and (2) available potential for substituting technological components (e.g. in buildings and energy and transport systems).

As a result of this techno-economic focus, various scholars have started a discussion on the interpretation of IAM scenario results (see e.g. Anderson and Peters (2016); Fuss et al. (2014); Kruger (2016)), especially as scenarios may present outcomes that could be controversial in the light of other criteria such as risk and societal support. For instance, researchers have pointed at the large-scale deployment of bioenergy combined with CO_2 capture and storage systems (creating so-called 'negative emissions') in most low-carbon scenarios in the 5th Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC) (Clarke et al., 2014). This requires moving towards unprecedented levels of human intervention, which raised questions among scholars about (1) the assumptions about the availability of these technologies and (2) the level of political (un)willingness accounted for in these modelled processes (Anderson and Peters, 2016; Geden, 2015; Peters, 2016). As IAMs do not account in much depth for various institutional, political, social, entrepreneurial and cultural factors, the scenario outcomes could be considered as offering a rather narrow technology-oriented perspective on transitions to low-carbon societies. In response to this caveat in IAM assessments on global change, various scholars have called for broader interdisciplinary research aimed at introducing more realism into IAM scenarios (e.g. Kruger (2016); Peters (2016); Stern (2016); Victor (2015)) to enhance the heuristic responses in IAM models.

In earlier work the IAM community has included elements of non-economic and non-technological motivation into its assessment. This led to the utilisation of various methodological approaches, each building on the existing conceptualisation of global systems change in integrated assessment modelling. Examples are:

- Using qualitative and comprehensive storylines that outline the considered socio-political development over time (e.g. as found in the Special Report on Emission Scenarios (SRES) or Shared Socioeconomic Pathways (SSP) (Nakicenovic et al., 2000; O'Neill et al., 2014));
- Using broader rule-sets in IAMs that are more reflective of real-world processes (such as the inclusion of limitations in joint international commitments and restricted availability of energy technologies, see e.g. Clarke et al. (2009); Kriegler et al. (2013); Kriegler et al. (2014b));
- Incorporating normative decisions for specific low-carbon transition strategies via participatory modelling with stakeholders (see e.g. Schmid and Knopf (2012), who demonstrate an application of stakeholder involvement in model-based analyses via an iterative process of dialogues);
- More explicit forms of modelling of non-economic motivations in IAMs by specifically designing various groups of consumers (see e.g. McCollum et al. (2016)).

Other attempts have focussed on expanding the current conceptual framework in IAMs by complementing default global IAM modelling efforts with insight from (1) other spatial levels (e.g. van Vuuren et al. (2007)) or (2) other analytical or disciplinary levels (e.g. by connecting to more detailed sector-specific or broader physical sphere models, see e.g. Deane et al. (2012); Drouet et al. (2005); O'Neill et al. (2014)).

Although these practices allow greater realism into the models' architecture, leading to better heuristic insights on long-term systemic change, the methodological approaches to enhance IAMs remain rather evasive of explicitly addressing or incorporating factors that shape particular changes within society, especially with respect to their role in transitions. IAM scenarios on low-carbon transitions may thus (1) expose a dominant focus on materialised changes without any notion of the instigators and incubators driving the change and therefore (2) reason on current power relations in society without allowing other forms of governance and development. As a result, transition processes remain mostly stylised in IAMs, which have yet only been explicitly addressed via scenario storyline descriptions in an ad-hoc manner (van Vuuren and Kok, 2015).

In this study, we attempt to go beyond the current state-of-the-art by developing mitigation scenarios by systematically drawing insights from socio-technical transition studies. More concretely, this study presents a practical application of combining the strengths of the quantitative techno-economic IMAGE/TIMER model (Stehfest et al., 2014) with qualitative insights from the Multi-Level Perspective (MLP) analyses (Geels, 2002; Geels and Schot, 2007). The study frames the transition towards a low-carbon society in the light of meeting the European Unions' long-term objective of lowering total domestic greenhouse gas (GHG) emissions by 80% in 2050 compared 1990 levels. Section 6.2 elaborates on identifying and utilising shared concepts of the considered techno-economic and socio-technical frameworks. Section 6.3 presents the scenario results in terms of energy supply and demand. Section 6.4 discusses the results and Section 6.5 summarizes and concludes.

6.2 Towards an interdisciplinary analytical framework and its operationalisation

6.2.1 Selection of analytical approaches

In this study we combine two analytical approaches which offer different but complementary views on the evolution of low-carbon transitions. We specifically focus on unifying insights gained from model-based analyses, providing insights on long-term techno-economic changes, with socio-technical insights providing detail on the role of technology, consumer behaviour, markets, institutions, infrastructure, business models, and culture in ongoing transitions.

A wide variety of model-based interpretations of systems change exist to date, ranging from (1) economic models, (2) energy system models and (3) integrated assessment models, each containing an unique blend of sectoral, technological, spatial and temporal detail (see e.g. Hourcade et al. (2006); Jebaraj and Iniyan (2006); Kriegler et al. (2015)). These differences allow to study specific concepts of interests, of which the latter is oriented towards providing insight on broader patterns of (global) systems change. Here, we predominantly focus on the TIMER model (Van Vuuren, 2007), an energy system simulation model representing simplified economy-environment causal chains, which is nested within a broader model-based framework on global systems change (IMAGE) (Stehfest et al., 2014). Combined, the TIMER/IMAGE[5] model is able to reflect year-to-year investment decisions and the implications to society based on specific rules about investment behaviour, fuel consumption and technological learning and diffusion patterns (Van Vuuren, 2007). As recent model developments have led to more explicit representations of sectors and actors (see e.g. Daioglou et al. (2012); de Boer and van Vuuren (2016); Girod et al. (2012); Isaac and Van Vuuren (2009)), the TIMER/IMAGE model provides opportunity to address social actor behaviour within the broader scope of global system change modelling.

5 Throughout this paper we may interchangeably refer to IMAGE/TIMER (the model) as well as IAM (the branch of integrated assessment to which the model belongs). Although all descriptions and statements in this study apply to the model IMAGE/TIMER, some broader statements can be applicable to the field of research.

In relation to socio-technical transition studies, a variety of theoretic frameworks have emerged in the last few decades that provide insights on social actor behaviour in, and the governance of, low-carbon transitions (see for an overview e.g. Markard et al. (2012)). The Multi-Level Perspective (MLP), as one of these theoretic frameworks, is a widely used analytical frame to study transitions (Geels, 2002; Geels and Schot, 2007), which recognises that transitions are non-linear processes that result from multiple endogenous and exogenous developments at three different analytical levels (the niche, regime and landscape level). For this study we selected the MLP as a perspective in transition research because it is fairly established within transitions studies and has (1) explicit consideration of the time dimension (linking future goals to near-term decisions), (2) relative narrative simplicity (e.g. struggle between niches and regimes in the context of slow-moving landscapes), (3) specification of systemic processes and underlying mechanisms, (4) explicit linkage of actors and material systems, and (5) supported the accumulation of historical insights that have the potential to inform future modelling efforts.

By combining these two analytical approaches in a wider heuristic framework, it creates a mesh of conceptualisations of physical and social systems change over time. Although the philosophies on system change between these approaches are acknowledged to be fundamentally different, several elements can be recognised that are in close proximity to each other, providing a promising starting point for further interaction. Given the differences in (1) assessment style (e.g. narrative-based vs. quantitative assessment), (2) analytical focus (e.g. emergent and disorderly developments vs. stylised and extended developments) as well as (3) the type of metric used to describe transitions (qualitative vs. quantitative descriptions of change), no full integration of both analytical approaches is pursued (Geels et al., 2016). We nonetheless agree with Turnheim et al. (2015) that '*there are good grounds for a common framing of analytical and governance problems [to] be addressed by combining different lenses and styles of explanation*" and describe a method for a softer integration of both transition conceptualisations in the following sections.

6.2.2 Defining shared concepts

A soft integration of IAM and MLP requires the identification of common concepts. In the formulation of both disciplinary philosophies we can detect several concepts that are considered key for both analytical approaches. These shared concepts provide some leeway for conceptual interaction. The following sections elaborate on these shared concepts.

6.2.2.1 Niche momentum and system inertia

A shared concept between the analytical approaches can be recognised in the way how systemic change is interpreted. Albeit with differences in semantics and differences in the exact connotations, we find that both analytical approaches more-or-less devise the concept of *niche momentum* (departure from the status-quo) and *system inertia* (stability and robustness of a regime to maintain itself) to explain systemic change. For example:

- MLP devises the concepts of momentum and inertia to describe the success or failure of interactions between actors and social groups, which help to explain how systemic change has materialised and what the ramifications are to the existing regime. The analytical emphasis of MLP is on qualitative elements, such as power struggles, emergence of networks and coalitions, vision development and learning processes (e.g. building new technical capabilities, learning about consumer preferences and market demand), and more generally on the co-evolution of change processes in multiple dimensions (social, technical, economic, political, cultural).

- IAMs devise the concept of momentum and system inertia to explain the rate of technological change over time, albeit with a more narrower interpretation of the causal mechanisms leading to such a new configuration and relying on historical evidence to provide the input for future change. For example, IAMs commonly utilise learning and logistic growth curves (and associated efficiency improvements and cost-reduction mechanisms) to endogenously represent the evolution of technological growth and diffusion. These conceptualisations of change inherently lean on simplified "outcome"-oriented representations of systems change, which may render out-of-date as soon as society shifts away from these deducted patterns of change (e.g. as a result of changing interests, collaborations, preferences, power struggles, etc.).

6.2.2.2 Transition narratives

Another shared concept is recognised in the effort to classify the course of systemic change in a so-called "transition narrative". Both analytical approaches devise (transition) narratives as a pragmatic research instrument to describe change, though each with a different purpose:

- The MLP perspective provides narrative *explanations* by focusing on interactions between niches, regimes and landscape. Given the rather intangible and fluid nature of many of the concepts addressed in MLP, the narrative approach offers the opportunity to codify and detect "generic" patterns that result from interactions between actors (e.g. groups making moves, taking actions and react to each other) (Geels and Schot, 2007).

- For IAMs, the narrative or storyline approach is generally used for those elements that cannot be directly addressed in quantitative mathematical formulations. Given how social actors and social activities find no direct analogue in IAMs, as they are implicitly encapsulated in the 'hard' technological and aggregated system processes and mathematical formulations, scenario narratives provide the opportunity to impose alternative sets of assumptions to model elements. The narrative approach allows for a more detailed description in the scenario logic, including elements such as lifestyle and governance style.

6.2.2.3 From shared concepts to conceptual interaction

In recognising and defining the shared concepts, it becomes clear that MLP embodies a wealth of information on the driving elements of socio-technical systems change, which are collected in a transition narrative to create a vast corpus of explanation on system change. Alternatively, IAMs contain a wealth of information on causal (techno-economic) interrelationships, which await corrective input to provide a (new) sequence of change over time. Given how IAMs are predominantly leaning on historical evidence in their conceptual interpretation of future change[6], MLP may provide a more forward-looking perspective on emerging developments. Conceptual interaction may therefore take the form of MLP informing IAMs with bottom-up insights on recent and emerging developments via notions on the direction, and unforeseen sources, of change for a wide range of niche-innovations. These notions may correct the stylised responses in IAMs which would otherwise remain guided by the techno-economic conceptualisation of systems change.

To remain compatible with and comprehensible to both analytical approaches, it is recognised that conceptual interaction needs (1) a level of simplicity (stylised but representative), (2) to take note of both bottom-up developments as well as top-down (landscape or system-wide) pressures over longer periods of time (which allow a departure away from the of existing system) and (3) to pay specific attention to core strategic agents of change (given the lack of representation of social actor groups in IAMs) (Berkhout and Turnheim, 2015). In that regard, we define two (polar) archetypical transition narratives which have been drawn from a typology of transition narratives by Geels and Schot (2007):

6 In more technical jargon, this reflects the process of calibration: although calibration may have been exercised with the latest state-of-the-art information on e.g. energy technology development, these quantifications remain reflective of materialised change during the preceding year(s).

- The first narrative (*Technological Substitution*) describes how stabilised niche-innovations are awaiting a window of opportunity to gain bigger market shares. This window of opportunity is described as a "specific shock" that initiates socio-technical change. The narrative represents a portfolio shift by regime actors, who are focussed on replacing existing socio-technical elements with versions that better fit with the new environment. Other elements (e.g. user practices, lifestyles, governance arrangements) remain close to the existing regime.

- The second narrative (*Broader Regime Change*) describes a lack of faith in existing regimes to respond appropriately to the new environment. It entails a shift to a new socio-technical system, based on the breakthrough of radical niche-innovations that entail not only technical changes but also wider behavioural and cultural changes and new user practices and institutions.

Both analytical approaches benefit from identifying niche-innovations as part of either one of these narratives. For MLP it allows to provide a frame to which real-world developments can be structured (via recurrent patterns and deviations), whereas IAMs can devise these transition narratives to distinguish between two different types of actors that drive systems change (namely (1) incumbent actors that are seeking a new balance within an existing regime, or (2) new actors that are destabilising the existing regime and replacing it with something new).

Together the analytical approaches are found to share conceptual space in (1) the run-up towards the present situation (with MLP "input" orientated and IAM "outcome" orientated) and (2) the interpretation of how systems will evolve over time (with MLP encompassing knowledge of the build-up and orientation of a variety of niches in becoming a dominant design that may challenge the existing regime, while IAMs depict the course of aggregated development for niche "families" within a broader spectrum of system development) (see Figure 6-1 for an illustrative example).

6.2.3 Operationalising the interaction

6.2.3.1 Drawing insights from shared concepts

To operationalise conceptual interaction between the two analytical approaches, a selection and study of multiple niche-innovations is required. These findings allow to create a typology of systemic change framed around the mutually shared concepts of "niche momentum" and "transition narrative".

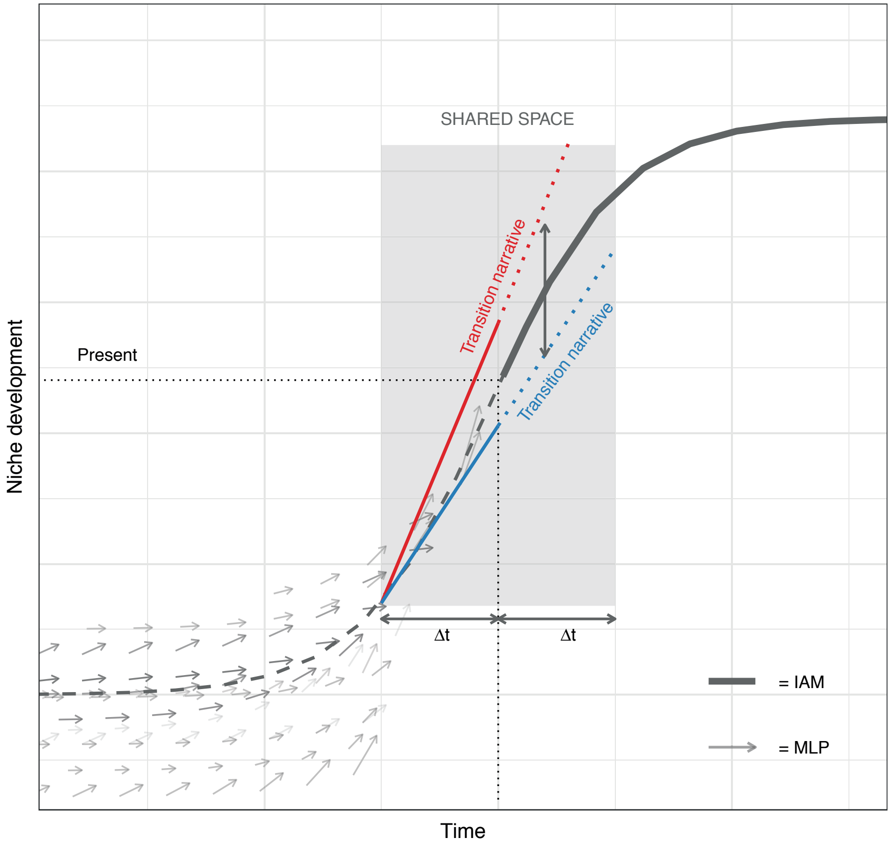


Figure 6-1 - Illustration of the two considered analytical approaches and their shared conceptual space. The arrows represent the various niche developments that can be studied with MLP. The line represent the stylised conceptualisation of system change based on historical "outcome" data (dashed) and the interpretation of the IAM on how it extends into the future (solid). Δt represents the considered timespan for study in MLP, of which is assumed that the current orientation of niches can be projected into the future. The red and blue lines represent the outcome of conceptual interaction, in which MLP can provide insight on (1) niche momentum (as represented in the slope of the line) and (2) the strategic actor driving a niche-innovation (as represented in the colour of the line). This information allows IAM analysis to adopt more forward-looking perspectives into projections, while accounting for specific actor bases.

- The selection procedure consisted out of a selective draw of case-studies within (1) numerous exemplar countries in Europe (respectively Germany, the Netherlands, United Kingdom and Sweden) and (2) three important economic domains (power, mobility, and heating). On average about 6-7 green niche-innovations have been selected per domain and country for further study. The niche-innovations varied in detail, ranging from specific technological niche-innovations to new methods and practices for mobility and heating (see Annex I table A1 for an overview).

- The study procedure consisted out of the analysis of three analytical dimensions, i.e. (1) innovation and market trajectories (techno-economic), (2) actors and social networks (socio-cognitive), and (3) governance and policies over the last 10-15 years. The dimensions combined led to an overall qualitative judgement of the current momentum of each niche-innovation, which is assumed to provide some indication of the potential towards the near future. Niche momentum could be judged as having "very low" (inert system) or "very high" (breakthrough) momentum with three intermediate values in between. In a similar fashion, the MLP assessment also provided insights on the subset of actors driving the change for niche-innovations by categorising the case-studies into either of the two transition narratives (respectively *Technology substitution* or *Broader Regime Change*).

The outcomes of the MLP assessments are visualised in Figure 6-2. The typology reveals that the various countries and domains are at varying stages of an energy transition. The electricity domains throughout Europe expose developments with medium to high momentum, signalling that a transition is eminent for these niche-innovations. Niches in the mobility domain are mostly ranked as having medium to low momentum, signalling that a departure from the established system is in a much earlier phase. Niches in the heating domain, however, depict low to very low momentum, suggesting an inert system that is not likely to adopt any new practices soon. In general, Figure 6-2 shows that for most behavioural change innovations, momentum is low. Interestingly, the niche-innovations are not uniformly classified to a certain transition narrative, implying that different motivations are driving niche-innovation development in different countries (for example, the development of onshore wind power has been mostly driven by incumbent actors in the UK, whereas the same niche was mostly adopted by new actors in Germany).

Despite the differences in "niche momentum" or "transition narrative" between the countries and between domains, several aggregated patterns can be deducted by equal weighing[7] of the results of the case studies on specific niches (represented by the bars in Figure 6-2). This reveals to what extent niche-innovations (1) are likely to gain momentum and (2) are developed by a specific set of actors driving the change.

7 One may argue whether equal weighing is an appropriate measure to draw notions of the course of change within different countries. However, given how each represented EU Member State is (1) bound to the same European GHG emission reduction target of 80% in 2050 compared to 1990 levels and (2) together represent a large share of emissions within Europe (representing ~40% of total European GHG emissions over the last 20 years), the collective action among these regions can be considered characteristic of the overall low-carbon transition strategy within the European context.

Ambiguous outcomes underline an important caveat in our approach, as currently we only draw information on emergent processes of change with a very prominent classification. Although we acknowledge that multiple interpretations are possible for depictions of strategic actors taking the lead, we leave a more pluralistic approach to future work. In the following section we elaborate on how these detectable patterns from MLP analysis were used to develop IAM scenarios.

6.2.3.2 Translating MLP insights into IAM analysis

The shared concepts are in a consecutive step translated into specific assumption-based changes to the models' quantitative parameterisation. Based on the detected patterns as presented in Figure 6-2, we are able to (1) allocate the developments for niche-innovations to a specific "transition narrative"-scenario (either *Technology substitution* or *Broader Regime Change*) and (2) modify the future orientation of a represented niche in the model via changes to the models' parameterisation.

- Regarding the allocation of niche-innovations to a specific "transition narrative"-scenarios, we have used the typology of Figure 6-2 as a guide to promote or weaken the representation of a niche-innovation in the respective scenario – as a unanimous allocation of a niche-innovation to either one of the transition narratives provides confidence that a transition is driven by a specific strategic group of actors.

- Regarding the representation of "niche momentum" in the model, we have used the typology to provide a forward-looking perspective on the development and orientation of the represented niche-innovation. If, for instance, strong inertia is observed in the MLP typology, this is translated in the scenario as a delay to the application of this niche.

In terms of actual implementation, every single parameter in the model reflects a lever that can be modified to impose control to the mechanisms of the model, which allows to change the course of direction by either promoting or moderating a specific behaviour (represented as the slope of the line in Figure 6-1). The question, of course, is across which range change is meaningful to represent the transition narratives. For example, if assumptions about efficiency clearly deviate from recent or local frontier developments, it is rather straight-forward to adopt new assumptions that reflect the more advanced real world processes. However, in cases where no quantitative information is available, or if the provided information does not allow to be translated to the mathematical formulations used in the model, more stylised methods need to be employed to impose a change. This is particularly the case for socio-technical processes representing elements like the accumulation of knowledge and the reordering of

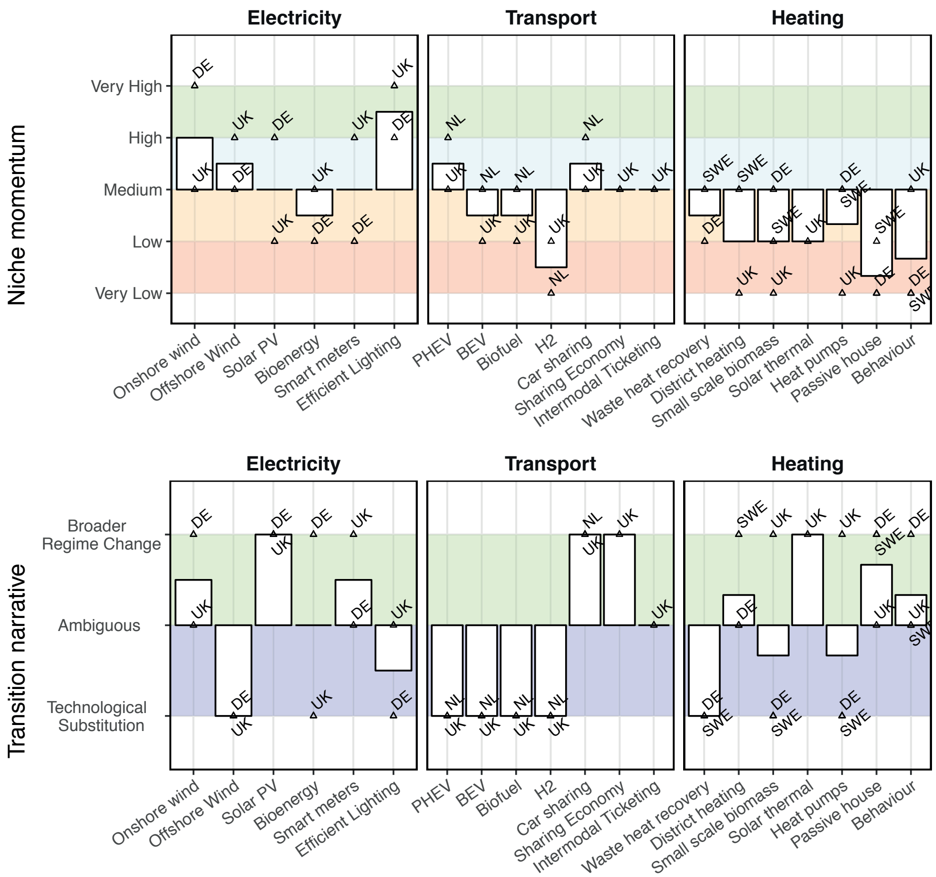


Figure 6-2 - overview of niche momentum and transition narrative per country (triangle) and the overall deducted patterns (bars). Electricity: DE (Rogge et al., 2015) UK (Geels et al., 2015). Mobility: NL (Turnheim et al., 2014) UK (Hodson et al., 2014). Heating: DE (Thema et al., 2014) UK (Turnheim and Berkhout, 2014) SWE (Nykvist and Dzebo, 2015). Abbreviations BEV: Battery Electric Vehicle. PHEV: Plug-in Hybrid Electric Vehicle. H_2: Hydrogen fuelled vehicle.

social rules. Although recent developments in the TIMER/IMAGE model created some opportunity to address social actor behaviour with more explicit detail (see van Sluisveld et al. (2016a) for more in-depth discussion), overall these elements may be represented in parameterisation methods that either *link* or *lock* specific dynamical processes in the model. An example of this is removing the relative cost differences for specific technologies in a portfolio (e.g. by allowing the higher levelised costs of electricity of offshore wind to converge to the lower levelised costs of electricity of onshore wind over time). This narrative-based assumption would imply an accumulation of interest, leading to faster runs through the innovation cycles than under default assumptions in the model. Alternatively, an example of locking, or changing societal rule-sets, can be considered by not allowing any further growth compared to a certain base year (e.g. no further growth of the household size beyond 40 m^2/cap in urban areas, as a "behavioural" change measure for the heating domain).

The "niche momentum" typology in Figure 6-2 provided the first indication of the degree of acceptable change. High momentum would reflect a change with more immediate effect in the model, whereas lack of momentum, such as considered for most behavioural change niche-innovations (see Figure 6-2), this would result in delayed effect. A full breakdown of specific assumption-based changes to the parameterisation of the TIMER/IMAGE model is presented in table B1 of Annex II.

Table 6-1 – overview of the scenario architecture

Transition narrative	Actor representation	Short name	Origin	Mitigation goal
Historical reference	-	2010	TIMER/IMAGE	-
Techno-economic optimisation	Rational-economic agent	*Default*	SSPs [1]	Global 2°C [2]
Technological substitution	Incumbents	*TechSub*	PATHWAYS[3]	-80% EU 2050
Broader regime change	New actors	*RegChange*	PATHWAYS[3]	-80% EU 2050

[1]For the purpose of this study we build on the new scenario framework for climate change research, also called Shared Socioeconomic Pathways (SSPs) (O'Neill et al., 2014). We select the middle-of-the-road narrative (SSP2) as the common storyline, representing a future with moderate mitigation and adaptation challenges (in terms of sustainable development, inequalities, technological change, and productivity of land).
[2] The mitigation goal here is defined as "Global 2°C" which represents a global commitment to limiting global warming to no more than 2°C in 2100 with respect to the pre-industrial level. In the conclusions of the 4th Assessment Report by the Intergovernmental Panel on Climate Change (IPCC), Annex-I (developed) countries were advised to reduce greenhouse gas emissions by 80%-95% in 2050 compared to 1990 levels as to remain aligned with the 2°C global objective (Council of the European Union, 2009; Gupta et al., 2007). As such, a global 2°C objective can be considered analogous to meeting the EU objective in 2050.
[3] These scenarios have been developed as part of the PATHWAYS project, which explored transition pathways to a low-carbon, sustainable Europe under different disciplinary lenses (Geels et al., 2016; Turnheim et al., 2015).

6.2.4 Defining transition narratives to a low-carbon Europe

By defining a trajectory of change, one can influence the course and the associated systemic responses embedded in the IAM modelling framework. In the current study, we emulate specific long-term normative (climate) goals by imposing exogenous influence on the techno-economic dynamics with the means available in IAMs, such as additional pricing policies that shift the balance in the models' choice mechanisms for technologies or services. In order to discuss low-carbon transitions in light of the European goal of reducing domestic reductions by 80% in 2050 compared to 1990 levels, we impose a continuous and increasing system pressure in the form of a carbon price[8]. This carbon price should be seen as a generic policy pressure leading to systemic behaviour oriented towards decarbonisation.

To consider the course of development for the new transition narratives, as well as to consider the relative difference to more conventional techno-economic model behaviour, we harmonise the system pressure to all scenarios so that European GHG emissions are reduced by 80% compared to 1990 levels by 2050. For the *Technological substitution* pathway, the required carbon price trajectory was found the be the same as under the default pathway, while in the *Broader regime change* pathway required a slightly higher carbon price to achieve a similar objective.

Apart from the specific narrative and assumption-based changes deducted from a typology as presented in Figure 6-2, we adopted two additional changes in the *Broader Regime Change* transition narrative. These additional constraints include no new construction of nuclear energy from the start of the simulation and no large-scale implementation of carbon capture and storage technologies, as both are difficult to combine with the *Broader Regime Change* transition narrative. Table 6-1 provides an overview of the scenario architecture of this study.

6.3 Findings on new transition pathways

In order to draw insights on the systemic responses of the TIMER/IMAGE model, we compare the emission pathways and the technology pathways between the different transition narrative scenarios. The first provides insights on the overall human-climate interactions over time, while the second provides detail on the sector and technology level (Rosenbloom, 2017).

6.3.1 Emission pathways

Achieving the European emission reduction objective demands a clear deviation from current emission levels (see Figure 6-3). Although by definition in all scenarios GHG emissions are reduced by 80% by 2050, the timing of emission reductions differs between the pathways. The new transition scenarios both show a faster reduction in emissions than the *Default* pathway, with the *RegChange* scenario showing the fastest reductions. These differences in emission pathways can be attributed to the

8 The common pricing policy assumed in IAMs is the so-called "carbon price" (or tax) which adds a disadvantage to technologies and services that devise fractions of carbon content within their functional unit. Although often called "carbon tax", this parameter may be interpreted in the widest form of top-down steering, and may therefore just as well represent other policy instruments leading to a cost-optimal implementation of policies.

specific assumptions imposed on technology growth and diffusion (*TechSub*) and to the assumed reduction in energy demand (*RegChange*). In the longer term (2050), the *Default* and *TechSub* scenarios describe a Europe with negative emissions from power production and strongly reduced emissions in the other sectors. Given the exclusion of negative emission technologies in the *RegChange* scenario, emissions in the other sectors are reduced even further than under the other two scenarios. Figure 6-3 also reveals that the main challenge for sectors is on mitigating CO_2 emissions, as non-CO_2 emissions show to be negated more rapidly.

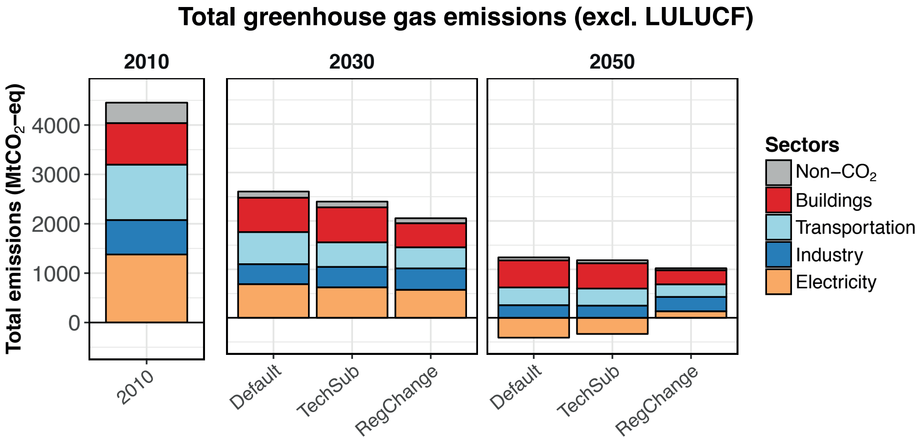


Figure 6-3 –Total greenhouse gas emissions for Europe disaggregated per economic sector, excluding emissions from Land Use, Land Use Change and Forestry (LULUCF). Sectoral emissions show total CO_2 emissions per sector, the sum of non-CO_2 emissions (representing CH_4, N_2O and F-gasses) are depicted separately.

6.3.2 Technology pathways

To compare the technology pathways between the three scenarios we devise total energy consumption of specific technologies and services (in EJ/yr) as the functional unit for comparison. Focussing on energy consumption allows inter-sectoral comparison of both (1) (fuel) substitution behaviour or demand reduction (as can be deducted in the absolute values) and (2) insights on niche momentum or system inertia (as can be deducted from the relative contribution to the total).

6.3.2.1 Sector-level changes

On the sector level we can observe the overall responses of the TIMER/IMAGE model in representing shifts in service demand, giving a first indication of shifted or maintained systems. In the *TechSub* and *Default* scenarios, efficiency gains lead to a lower total energy demand in 2030 than in 2010, with no major difference between these scenarios (see Figure 6-4). The *RegChange* scenario depicts larger reductions in total energy demand, mainly due to 1) lower household energy consumption as a result of lower space heating demand, and 2) lower energy consumption in transport as a result of reduced passenger air and road travel. Over the longer term, total energy demand only decreases slightly further, with the largest reductions again taking place in the *RegChange* scenario. Interestingly, the *TechSub* and *RegChange* scenarios become less dependent on liquid energy carriers than the *Default* scenario. For the *TechSub* scenario this can be explained by accelerated electrification in the transport sector, while in *RegChange* scenario this reduction represents a drop in air travel and an increase in public transport (train). In the *RegChange* scenario gaseous fuels are reduced more strongly than in the other scenarios as a result of a lower demand for space heating.

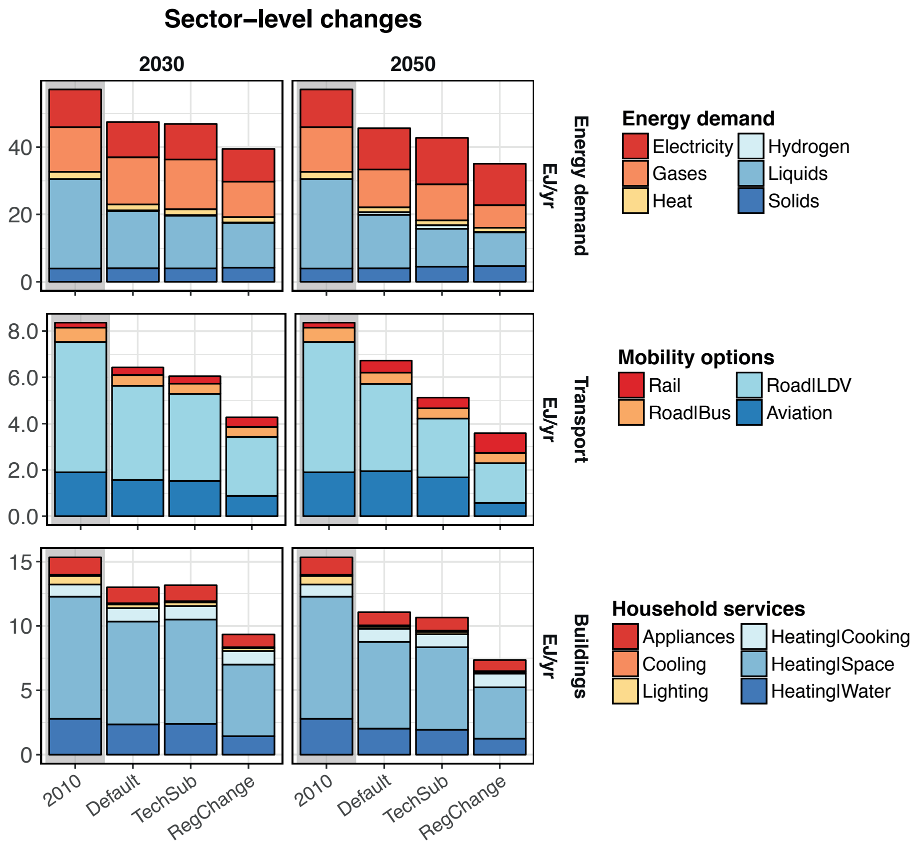


Figure 6-4 - Total final energy demand for each resource and total demand for transport and residential sector services in Europe.

6.3.2.2 Technological configurations

Until 2030, both the *TechSub* and *RegChange* scenarios show no substantial deviations for the power sector compared to the *Default scenario*. This implies some systemic inertia, which can be attributed to the lifetime of existing capital and the postponement of new investment decisions by no sooner than 2025-2030 in the model (regardless of the scenario assumptions). Due to the lower capital lifetime of cars compared to power supply capital and infrastructure, inertia plays a much less important role in the transport sector, which is visible by the completely different private vehicle pool in the *TechSub* scenario by 2030, both compared to 2010 and to the other scenarios. Under the *RegChange* scenario the private vehicle pool is not substantially different than under the *Default* scenario, though total energy demand is much lower as a result of changes in demand and mode split (presented in Figure 6-4). For the heating domain, all scenarios depict a dominant and even increasing role for natural gas in space heating in the short term.

In the longer term to 2050 TIMER/IMAGE shows a shift to renewable energy technologies, in particular onshore wind, under the *Default* scenario settings. Under the *TechSub* scenario assumptions, the created preference for off-shore wind is clearly represented over time, while the preference for distributed and decentral solutions is seen in the *RegChange* scenario (as reflected in the relative contribution for solar power and onshore wind). Although nuclear power has been explicitly restricted only in the *RegChange* scenario, nuclear energy shows to be phased-out in the other transition narratives as well. In the *Default* and *TechSub* scenario, this appears to be substituted for fossil and bioenergy-based thermal power supply with carbon capture and storage (CCS) systems, which could be devised as spinning reserve to balance shortages in supply from the more intermittent energy sources. The *RegChange* scenario, on the other hand, depends more on intermittent energy technologies, showing only marginal contribution of other technologies (such as bioelectricity and hydro power).

The effects of the transition narratives are also visible for specific demands, such as private road travel and heating. We find that under the *Default* scenario the (gasoline-based) internal combustion engine (ICE) vehicle is maintained, with only some marginal diversification in the passenger car fleet by 2050. This is in stark contrast with the *TechSub* scenario, in which the battery electric vehicle (BEV) has almost fully overtaken the private vehicle pool for road travel. The *RegChange* scenario is characterised by major reductions in total energy use for passenger vehicles as a result of behavioural change. Interestingly, although a scenario without "negative emission" technologies (*RegChange*) would necessitate the greater electrification of energy demand sectors, some dependency remains on gasoline-based vehicles by 2050 (as a result of higher electricity prices). For heating, some rebound effects can be observed in the *TechSub* scenario, given the increase of oil-fired and gas-fired boilers compared to the *Default* scenario, indicating that electrification in some areas leads simultaneously to the strengthening of existing fossil-based regimes elsewhere. Only for the *RegChange* scenario some momentum is depicted for the considered niche-innovations, as "small scale biomass" and the "heat pump" (denoted as ASHP (air source heat pump) in Figure 6-5) find some market share. The findings underline that the buildings domain is strongly inert; however, it should also be noted that the TIMER/IMAGE model has only a limited representation of the considered building stock and lacks explicit detail on the technology-level.

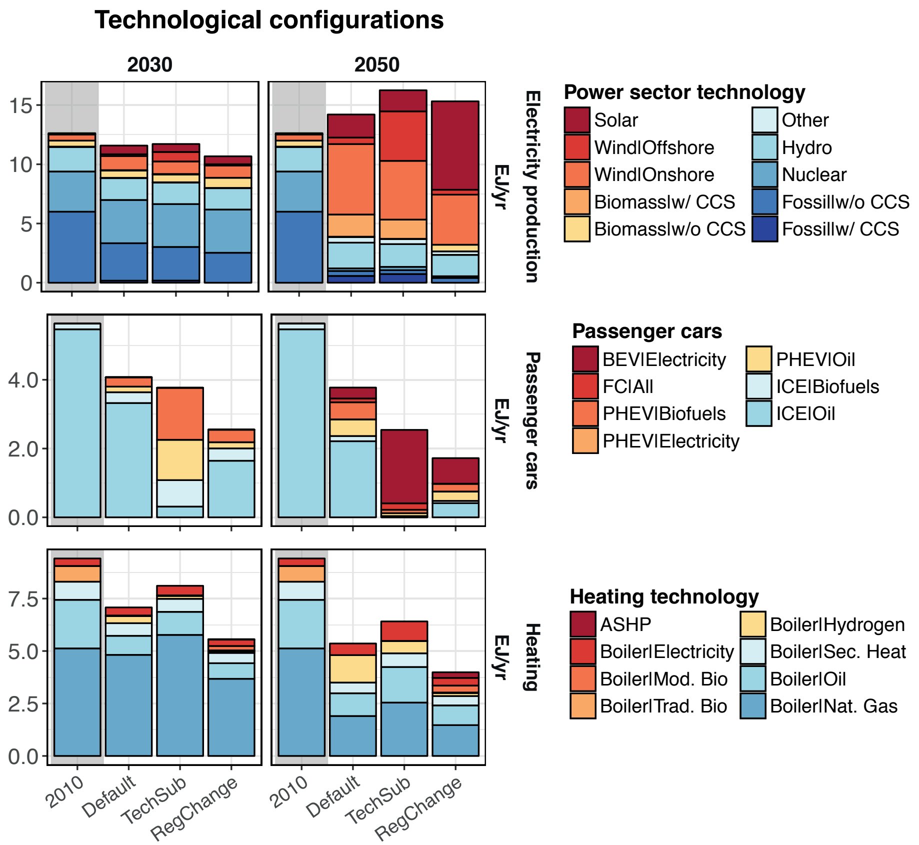


Figure 6-5 - Technology change for the power sector, passenger cars and heating technologies in Europe. CCS: carbon capture and storage. BEV: Battery Electric Vehicle. PHEV: Plug-in Hybrid Electric Vehicle. ICE: Internal Combustion Engine. ASHP: Air-source Heat Pump. Boiler|Mod.Bio: (advanced) biofuel-powered boilers/ Bioler|Trad. Bio: Boiler powered on wood pellets.

6.4 Discussion

In this study we have presented a method which allowed a conceptual interaction between integrated assessment modelling and insights of the multi-level perspective. The conceptual interaction resulted in two distinct transition narrative scenarios with specific detail on (1) the momentum of various niche-innovations in three different economic sectors and (2) a notion of strategic actors driving the change. The implications of these transition narratives have been further studied by adjusting the TIMER/IMAGE model to account for these low-carbon transition developments. Although earlier work has focussed on narrative-driven scenarios and more explicit narrative-driven notions of actors, these scenarios have mostly addressed (1) actors in a more generic style (e.g. van Asselt et al. (1996)), or included (2) stylised storylines on future movements (Kriegler et al., 2014a; Nakicenovic et al., 2000; O'Neill et al., 2014). In the *current* work we go beyond the existing work as we have specifically 1) included a more realistic representation of agents driving the change and 2) derived and implemented a notion of current-day (transitional) movements into the scenario architecture. As a result, the application represents a method in which socio-technical transition studies can provide guidance to integrated assessment modelling to represent more heuristic systemic change over time.

However, although integrated assessment of global change is interdisciplinary in nature and has a long tradition in unifying research communities to strengthen the understanding of global change (Weyant, 2009), each disciplinary expansion wagers the question whether the new disciplinary knowledge has been implemented appropriately and whether it adds value to the broader knowledge base. Several methodological challenges have been faced to operationalise the presented conceptual interaction:

- A first methodological challenge relates to the interpretation of detailed information from MLP assessment. In order to assess the impact of the transition narratives over time with an IAM model like TIMER/IMAGE, this required to (1) draw a uniform direction of change for each scenario and therefore (2) assume scalability and comparability of case-study results as to fit within the European resolution of the model. This is a deliberate narrowing of the richness and qualitative detail of the MLP assessments. In that regard, the established operational link is rather deterministic and static in nature, even though it is acknowledged that socio-technical elements are more volatile and may change over time. It remains arguable whether this resulted into a representative reflection of the collective movement in Europe. However, given the exploratory nature of this study, the actual representativeness of the scenarios have been considered secondary to studying the models' responses under more specified socio-technical input. As such, the transition narrative scenarios have been more instrumental to mirror and strengthen the analytical understanding of required (socio-technical and techno-economic) systems change in a more broader context.

- A second methodological challenge relates to the prevailing techno-economic focus in explaining low-carbon transitions. This techno-economic orientation may be a result of “availability” biases in both analytical approaches, which imposes restrictions to how transitions and responses are explained in the current results. For example, the selection of case-studies shows a preference for (1) technological substitution niche-innovations, (2) small-scale innovations over more large-scale system changes, and (3) existing concepts rather than new and disruptive innovations. Conversely, in their limited technological, spatial and actor-related resolution, IAMs focus on processes that are very thoroughly or explicitly modelled, such as large-scale, centralised, technologies (represented by the preference for “negative emission” technologies). Hence, as notions of future broader regime change are not explicitly represented in observational data or modelled in IAMs, it leaves many questions relating to future (1) steering of socio-technical potential, (2) representations of new systems, and (3) negating the climatic response beyond 2050 largely unanswered.

To summarise, although our effort to align IAM with MLP has not been without its challenges, defining several operational links in a participatory manner has created new avenues for interaction between the two research communities and propagated discussion on the appropriateness of several long-term transition depictions. As such, our approach answered to calls for IAMs to engage further and deeper with social sciences (Victor, 2015). At the same time, further methodological development is recommended.

6.5 Conclusions

Integrated Assessment Models of global change (IAMs) contain a wealth of information on the interrelations and feedbacks within and between natural and human systems. However, devising aggregated formulations of systems change in mathematical formulations and projecting these developments into the future leaves room for debate on the representation of (1) actual system change and (2) the drivers of systems changes. Earlier work has focussed on improving (modelling) or framing (scenario narratives) a course of systemic change, though remained evasive of explicitly addressing factors that shape change within society. In this study, we have introduced and applied a method to use insights of socio-technical transition studies (MLP) to inform model-based analysis (IAM) on the agents driving change while explicitly accounting for their effect on current system change. The study allows us to draw the following lessons:

MLP can function as a useful heuristic for IAMs to analyse new and emerging directions of change

By systematically and consistently assessing a variety of niche-innovations across a range of European countries with MLP, it provided a (1) snapshot of the assumed current momentum in a wide range of niche-innovations and (2) a classification of the strategic actors mobilising a prospective transition (limited to incumbents and new actors). The results have powered two fundamentally different transition narrative scenarios with respect to the role of actors, the role of governance and the kind of technologies being considered, whose impact to long-term future system change could be assessed with the TIMER/IMAGE model. The resulting transition narratives specifically allowed for a gradual and mixed implementation of impulses reflective of actual change in otherwise rather stylised representations of change in model-based scenarios. Although the conceptual interaction between MLP and IAM enabled to mirror and analytical strengthen the general understanding of needed (socio-technical or techno-economic) systems change, several methodological challenges have been left unresolved. Hence, future research could focus on further systematic (joint) development of the methodology to further explore the effect of social actors in driving future low-carbon change.

Different pathways are compatible with meeting the 80% emission reduction target in Europe by 2050

The modelling exercise revealed that different transition pathways could meet the EU 2050 objective. In the rationale of the considered transition narratives and as part of the mechanics of the TIMER/IMAGE model, this resulted into an explorative exercise on how a long-term objective could be met in the presence or absence of "negative emission" technologies. In the presence of such technologies, the transition narrative scenario is framed around technological substitution methods, resulting into a more rapid decarbonisation of the power supply sector and sinking the carbon emissions via carbon removal and storage technologies. In the absence of such technologies, intermittent renewable energy technologies and demand reductions via behavioural change are notably more important to remain aligned with the EU 2050 objective. Despite assumed low momentum for behavioural change niche-innovations in the present, the effect of demand-oriented solutions on reducing emissions is considered significant for those sectors and services that are in close proximity to the user (respectively heating and transport). In both transition narrative scenarios, additional system pressure has been imposed to align current systems with either a more rapid technological transition (technology substitution) or to ensure that new actors can play a more important role (broader regime shift).

Greater focus needed on demand-oriented solutions in techno-economic assessment

Although the transition narratives have changed the responses of the TIMER/IMAGE model, most of the demand-oriented solutions find implementation via ad-hoc and assumption-based changes. As such, transition narratives that are dependent on more socio-cognitive changes or overall broader regime change may find only limited representation in techno-economic assessment. This leaves many questions relating to future (1) steering of socio-technical potential, (2) representations of new systems, and (3) negating the climatic response in the absence of "negative emission" technologies largely unanswered. These limitations should be devised as encouragement to pursue further development in this direction.

Acknowledgement

The research leading to these results has received funding from the European Union Seventh Framework Programme FP7/2007-2013 under grant agreement n° 603942 (PATHWAYS).

Annex I: Niche-innovations and availability in TIMER/IMAGE

Table A1 – Overview of considered niche-innovations and the representation thereof in the TIMER/IMAGE model. Blue rows represent those niche-innovations that have been subjected to MLP assessment and find application in the TIMER/IMAGE model.

Domain	*Niche-innovation*	*Subcategory within the niche*	*Representation in TIMER/IMAGE*
Electricity	Biogas	Landfill gas	NO
		Biomass	NO
	Storage facility	Power to gas	NO
		Batteries	NO
		Seasonal pump storage	NO
		Hydrogen	NO
		AA-CAES	NO
	Fuel cells		NO
	PV	Rooftop	NO
		Field	YES
	CSP		YES
	wind	Onshore	YES
		Offshore	YES
		Small-scale wind	NO
	CCS		YES
	Micro-generation	Micro-CHP	NO
		Virtual power plant	NO
	Geothermal		YES
	Wave/tidal power		NO
	Fusion		NO
	Small-scale hydro		NO
	Demand response / Smart grid	Smart homes (smart meter)	IMPLICITLY
		Heat pumps	NO
		Power to heat	NO
		Smart charging e-vehicles	NO
		Vehicle-to-grid (V2G)	NO
		Industry-specific	NO
		CFL an LED lighting	YES
	Grids	DC transmission systems	NO
		Variable transformers	NO
		Underground cable	NO

Domain	Niche-innovation	Subcategory within the niche	Representation in TIMER/IMAGE
Mobility	BEV	Battery electric vehicles	YES
	Biofuel	Biofuels	YES
	H_2	H_2 fuel cell vehicles	YES
	PHEV	ICE/electric hybrid vehicles	YES
	Lifestyle related	Private mobility on demand (from ownership to service on demand) multiple modes	IMPLICITLY
		(safe & convenient) urban and peri-urban cycling	NO
		Inter-modal transport	NO
		Compact cities	IMPLICITLY
		Remote working, shopping, etc	IMPLICITLY

Domain	Niche-innovation	Subcategory within the niche	Representation in TIMER/IMAGE
Buildings/ Heat	Biogas	Biogas/biomethane injection	YES
	Storage	Power to gas/heat	NO
	Renewable heating	Solar thermal heating (collectors)	IMPLICITLY
		Solar hot water heaters	IMPLICITLY
		Waste water heat recovery	NO
		Small biomass	IMPLICITLY
		Combined heating (cooling) and power (CH(C)P)	NO
	Heat generation	Geothermal heating	NO
		District heating	IMPLICITLY
		Virtual power plant	NO
	Insulation	Insulation of hot water pipes	IMPLICITLY
		Insulation of exterior walls, basement, roofs	IMPLICITLY
		Greening exteriors and roofs (also for cooling)	IMPLICITLY
	Ventilation	Efficient mechanical HVAC systems	IMPLICITLY
	Energy efficiency	Efficient, condensing boilers	IMPLICITLY
		Heating control systems (smart meters)	NO
		Heat pumps	YES
	Behavioural	Lower indoor temperature (thermostats)	YES
		Lower size of dwelling p/cap	YES
		Behaviour change campaigns	IMPLICITLY
	Building standards	Low-energy, zero/plus-houses	YES

Annex II: Changes to parameter settings of TIMER/IMAGE

Table B1 - overview of implemented assumption-based changes to the TIMER/IMAGE model

	TIMER/IMAGE	
	Technological substitution	**Broader regime change**
Landscape		
Climate policy	Global carbon price aligned to long-term macro-political agreement	Global carbon price aligned to long-term macro-political agreement
Electricity sector		
Onshore wind		
Offshore wind	LCOE for offshore wind equal to onshore wind	
Solar PV		Grid parity is reached for solar PV by 2040
Bioenergy		
Nuclear		Normative decision to phase out nuclear (No new capacity) after 2010
CCS		Normative decision to not embark on CCS
Transport sector		
(Plug-in-)Hybrid Electric Vehicles	25% purchasing price subsidy	
Battery Electric Vehicles	25% purchasing price subsidy	
Biofuel combustion engines	25% purchasing price subsidy	
Hydrogen fuel Cells	25% purchasing price subsidy	
Car sharing		Increased vehicle occupancy rate
Other		Reducing available travel budget per person Increased preference for public transport
Buildings sector		
Low-energy housing		15% energy reduction due to improved insulation
Behavioural change/ Smart metering		1. Change temperature setting by 1°C starting at 2011 2. Switch-off standby mode appliances by 2013 3. No growth of appliance ownership after 2013 4. Phase-out of tumble dryer by 2030 5. More efficient use of appliances from 2013 onwards 6. Shower 2 minutes less from 2013 onwards

Table B1 - overview of implemented assumption-based changes to the TIMER/IMAGE model (continued)

	TIMER/IMAGE	
Lower size of dwelling		People do not move to bigger house with increasing income by 2025 (dimensions converging to 50m^2/cap in rural and 40m^2/cap in urban areas)
Waste heat recovery	Improved secondary heat efficiency (45%)	

Chapter 7

Low-carbon strategies towards 2050: comparing ex-ante evaluation studies and national planning processes in Europe

Submitted, in review *van Sluisveld, M.A.E., Hof, A.F., van Vuuren, D.P., Criqui, P., Matthes, F.C., Notenboom, J., Pedersen, S.L., Pfluger, B., Watson, J., Boot, P. (submitted) "Low-carbon strategies towards 2050: comparing ex-ante evaluation studies and national planning processes in Europe "*

Abstract

Both the European Union as well as the Member States have often used techno-economic modelling studies to analytically underpin the ex-ante policy evaluation of proposed low-carbon strategies. These studies vary in depth, focus, and degree of embedment into policy design. In this study, we systematically look into these differences by comparing the long-term perspectives toward 2050 of five EU countries, respectively Denmark, France, Germany, the Netherlands and the United Kingdom, in a two-step approach. The study draws insights on i) how ex-ante policy evaluation efforts are mobilised and ii) whether the national approaches are consistent with long-term European policy objectives for 2050. The first step consists of a qualitative comparison of (1) the governance of ex-ante policy evaluation in long-term policy planning processes, (2) the distribution of knowledge and skills for ex-ante policy evaluation, and (3) the inclusion of (public) stakeholders. The second step consists of a quantitative comparison of national model-based ex-ante policy evaluation studies to assess (1) their alignment to communicated long-term ambitions and (2) the relative differences. We find a high diversity in national configurations on planning towards 2050, for instance regarding the degree of institutional embedding (e.g. by the presence or lack thereof of climate regulations and monitoring and advising organisations) and the distribution and utilisation of model-based ex-ante policy evaluation efforts. Interestingly, while the national ex-ante policy evaluation studies provided insights into the required domestic action, very little attention was given to the alignment of domestic policies with European or global mitigation ambitions. This study concludes with several areas in which ex-ante policy evaluation could be strengthened.

Keywords: climate and energy policy, decarbonisation strategies, ex-ante policy evaluation, integrated assessment modelling

7.1 Introduction

In order to track the progress on mitigating greenhouse gas (GHG) emissions, the European Union (EU) has established various regulations and reporting obligations for Member States to monitor current trends (ex-post evaluation) as well as to articulate on prospective trends (ex-ante evaluation) (EC, 2004). Most of these established monitoring and reporting efforts have focused on documenting (national) GHG emissions and the implemention of the Kyoto Protocol (European Union, 2013). However, new challenges for monitoring and reporting have arisen since the adoption of the 'Climate and Energy package' in 2009 (European Union, 2009a, b, c), which introduced new policies and legally binding legislation related to the GHG and renewable energy targets. For example, the EU Renewable Energy Directive (RED), as one of the new policies in the 'Climate and Energy package', has been translated into various National Renewable Energy Action Plans (NREAPs), which outline the national ambitions for utilising renewable energy by 2020. Likewise, Member States have adopted national (non-binding) commitments for 2020 on total primary or final energy consumption as part of the EU Energy Efficiency Directive (EED) (EEA, 2014). As a result, these specific ambitions and commitments have been monitored for progress over time.

As these targets for 2020 need to be seen in the broader context of meeting long-term ambitions, such as the commitments for 2030 (GHG emission reductions of 40% compared to 1990) (European Commission, 2014), 2050 (GHG emissions reductions of 80%-95% compared to 1990) or the end of the century (well below 2˚C) (European Commission, 2011), greater planning, coordination and documentation efforts of both the EU and the Member States are required. This is acknowledged in the EU 2030 framework (European Commission, 2014), in which the European Commission proposed a new governance scheme that recognises quantitative ex-ante evaluation of national climate and energy plans as an operational element in gaining insight on meeting long-term (supranational) targets (European Commission, 2016). Furthermore, in line with the EU 2030 framework, the EU Energy Union has been established to streamline and integrate a series of policy frameworks into one cohesive strategy. As part of this, Member States are asked to prepare national energy and climate plans with quantified detail towards 2030 and a more in-depth perspective towards 2050. These plans are intended to warrant consistency of national commitments to EU policy objectives (European Commission, 2015).

Given the recent nature of planning towards 2050 on the national level, we present an overview in this paper of the various routes taken by various EU Member States. The main research questions of this study are as follows:

- How are ex-ante evaluation efforts organised in different European countries?

- Are existing representative national scenarios towards 2050 consistent with the long-term European ambitions for 2050?

We focus on five EU Member States (respectively Denmark, France, Germany, The Netherlands and the United Kingdom) which together account for 52% of total GHG emissions in the EU in 2014 (EEA, 2016). As such, the collective movement of these governments is considered important in the light of meeting the EU 2050 objective. Moreover, the sample includes northern European countries who have been drivers of the EU climate policy agenda (Germany, UK) (Jordan and Liefferink, 2004) which provide an experience base in establishing and evaluating long-term policies to which other countries can be compared and contrasted.

7.2 Methodology

7.2.1 Qualitative evaluation of national long-term policy planning

Planning towards 2050 is a difficult exercise given the lengthy timeframe and the volatility in political, social, and technological development over time. In literature three elements are recognised that are assumed to warrant effective and durable coordination of long-term ambitions: (1) strengthened institutions, to provide a robust platform for development, (2) expanded governmental and non-governmental capacity, to draw momentum and resources, and (3) routinized environmental performance reviews, to signal deviations and re-enter issues on the political agenda if necessary (Hovi et al., 2009). In order to gain insight into how Member States are organising long-term policy towards 2050, we draw a typology based on these qualitative elements. We specifically focus on (1) the governance and institutional arrangements of long-term ambitions and the ex-ante policy evaluation of long-term ambitions and (2) the distribution of knowledge and skills used to underpin long-term policy choices. Moreover, as the European Union requires the active engagement of (public) stakeholders in national planning processes (principle of subsidiarity) (European Union, 2012), we also consider how participatory processes contribute to ex-ante policy evaluation. Insights are gathered by means of a literature research looking into (a) national and European policy documents, (b) research papers and (c) national regulations. We specifically looked for information on the (i) organisations (legally) involved and (ii) methods and techniques used in ex-ante policy evaluation studies. Additional insights on national policy contexts have been drawn via an expert workshop, organised in June 2016, inviting national policy makers and experts familiar with exercising ex-ant policy evaluation studies (as documented in van Sluisveld et al. (2016b)).

As rich literature is already available on the evolution of national policies over time (see for example Fabra et al. (2015); IEA (2013, 2014); Notenboom et al. (2012)), the qualitative evaluation does not attempt to provide an exhaustive overview of previously or currently implemented policies on the national level. Instead, we attempt to yield insights by looking at various countries in a birds-eye perspective approach to consider *how* long-term planning for climate and energy policy and ex-ante policy evaluation are devised.

7.2.2 Quantitative evaluation of ex-ante policy evaluation studies

To complement the qualitative evaluation we also consider the content in national model-based ex-ante policy evaluation studies, which provide more quantitative detail on considered national policy directions. For simplicity, we assume that model-based scenario analysis via the use of advanced modelling tools is the main instrument to exercise quantitative ex-ante policy evaluation (although other tools and methods may be used, as elaborated on in Nilsson et al. (2008)). All the countries under study have proven experience in developing model-based ex-ante policy evaluation studies given their use in the past to underpin policy decisions. We distinguish between two types of model-based scenario analyses; those designed by (national) research groups to look into national developments over time (national model-based scenario studies) and those that have been designed to study broader developments throughout Europe as a whole (European model-based scenario studies).

7.2.2.1 National model-based scenario studies

Given how national ex-ante policy evaluation studies are yet to be submitted to the EU Energy Union, we draw insights from existing model-based ex-ante policy evaluation studies. For practical reasons, we have selected one representative national ex-ante policy evaluation study per country, illustrating a number of policy scenarios in line with the EU 2050 ambitions (see Table 7-1 for an overview). To warrant the representativeness of the current national policy discourse for long-term planning in these studies, we selected studies that (1) are conducted relatively recent, (2) include a time horizon of up to 2050 and (3) include quantitative detail with regard to their respective assumptions and results.

Figure 7-1 - Overview of resources used and their defining characteristics.

	Denmark	France	Germany	The Netherlands	United Kingdom
Contributing Institute(s)	Danish Energy Agency	ANCRE	Öko-Institut Fraunhofer-ISI	PBL / CPB	UCL / UKERC
Mitigation scenarios [number consistent with EU 2050 goal]	4 [4]	4[4]	2 [2]	4 [2]	5 [2]
Year of publication	2014	2014	2016	2015	2016

For *Denmark*, we have selected the multi-pathway assessment of the Danish Energy Agency (2014). As the Danish Energy Agency (DEA) is a governmental agency, national model-based analyses by the DEA have usually been subjected to approval processes involving the minister and various stakeholders and research institutions, which creates some legitimacy to being representative for the Danish future outlook. Moreover, all the scenarios in this study aim for a fossil-fuel independent energy system, which is consistent with the current policy direction.

For *France*, we focus on four marker scenarios which have been identified during the *National Debate on Energy Transition* in 2013 (Grandjean et al., 2014). These scenarios have been drawn from fifteen pre-existing French national energy scenarios that include an outlook towards 2050, which have been created by multiple private and public research and governmental agencies. The marker scenarios represent four stylised pathways towards meeting the French GHG emission reduction target of 75% in 2050, which differ in focus on how to transform the French energy system (varying in terms of high and low energy demand reduction, and high and low shares for nuclear energy in total power supply).

As a representative *German* national scenario study, we have selected the "*Climate protection scenario 2050*" study (Öko-Institut / Fraunhofer ISI, 2016). Within this study two scenarios are provided that respectively aim for 80% and 95% GHG emission reductions by 2050 relative to 1990 levels, without deploying nuclear energy and carbon capture and storage technologies in power supply. The scenarios have been commissioned by the *Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety* (BMUB), and developed in a research consortium as part of a broader modelling exercise (see e.g. Öko-Institut / Fraunhofer ISI (2014, 2015, 2016)), linking a variety of different modelling instruments with different focus areas together (Hillebrandt et al., 2015).

As a representative *Dutch* national scenario study we have selected two scenarios from the '*Welvaart en Leefomgeving*' study that align to the EU 2050 ambitions of meeting the 80% GHG emission reductions (*Centraal* and *Decentraal)* (Matthijsen et al., 2015). The scenarios were commissioned by the *Ministry of Economic Affairs* and the *Ministry of Infrastructure and Environment* and provide the analytical underpinning for the Dutch long-term vision as presented in the *Energy Agenda* for 2050 (Ministry of Economic Affairs, 2016).

For the *United Kingdom* we have selected the scenarios by McGlade et al. (2016) that meet the 80% GHG emission reduction target (respectively *Maintain* and *Maintain (Tech fail)*) as representative national scenarios for this study. These scenarios respect official UK short-term and long-term targets on emission reductions and have been produced by the same model (UKTM) as the one used to inform decisions about the *fifth carbon budget period* (Pye et al., 2015). The scenarios embed explicit assumptions on not allowing new capital construction for coal (*Maintain*) and assuming no commercialisation of carbon capture and storage (CCS) technologies in the near future (*Maintain (tech fail)*). One unpublished additional scenario of the same modelling exercise has been included (*Late catch-up*), representing higher emissions during the *fifth carbon budget period* but higher mitigation efforts after 2035.

7.2.2.2 European model-based scenario studies

Complementary to the national model-based scenario studies, we also include the outcomes of European model-based scenario studies. European model-based analyses allow us to gain further insights on the relation of cross-border topics to meeting a collective EU objective, such as the trade of electricity and effort sharing. For this study we draw from the multi-model inter-comparison project EMF28 (Weyant et al., 2013); a project by the *Energy Modelling Forum* that specifically focused on the European policy context. We have selected a scenario that considers optimistic assumptions on technological availability, techno-economic improvements for renewable energy technologies, nuclear power deployment based on merit and cost-performance and an energy intensity improvement of 20% relative to business-as-usual assumptions (denoted as "80% EFF" in Knopf et al. (2013)).

The "80% EFF" scenario has been selected for its comparability to the European and national policy directions for the selected countries in *this* study, both in terms of respecting the EU GHG emission reduction goal in 2050 (80%) as well as in aligning with considered national low-carbon strategies without foreclosing any specific ones over time (such as nuclear energy and CCS deployment) (Knopf et al., 2013). Differences occurring between these projections and the depicted national projection could originate from, amongst others, 1) the use of different models, 2) the use of different (national) statistics, 3) different interpretations of specific national policies and 4) differences in assumed long-term national ambitions and international collaboration.

7.3 Results

7.3.1 Qualitative evaluation of national policy planning

This section draws a typology of the national policy planning contexts of the five countries considered in this analysis. In the following sections we will elaborate more in-depth on the governance of ex-ante policy evaluation in long-term planning, (2) the distribution of knowledge and skills used to underpin long-term policy choices and (3) the involvement of (public) stakeholders in long-term policy planning processes. The results have been summarised in Table 7-2.

Table 2 - Overview of national policy planning contexts and ex-ante evaluation configurations per country.

	Denmark	France	Germany	The Netherlands	United Kingdom
			Governance of ex-ante policy evaluation		
2050 policy plan (year of publishing)	Energy Strategy 2050 (2011)	National Low-carbon Strategy (2015)	Climate Plan 2050 (2016)	Energy Agenda (2016)	Carbon Plan (2011)
Institutional arrangements (Year of adoption)	Climate Change Act (2014)	Energy Transition for Green Growth Act (2015)	None (but decisions require inter-ministerial approval)	None (proposed)	Climate Change Act (2008)
Advising body (year of establishment)	CCC (2015)	CETE (2015)	No (but inter-ministerial approval)	No (but part of 'planning agencies')	CCC (2008)
Explicit ex-ante evaluation in policy design	Yes	Yes	Yes	Indicative planning	Yes
			Distribution of ex-ante evaluation knowledge and skills		
Government institutes	Yes	Yes	No	Yes	Yes
Academic institutes	Yes	Yes	Yes	No	Yes
Other institutes	Yes	Yes	Yes	Yes	Yes
			Stakeholder engagement		
Public dialogue (Year)	Yes (2009)	Yes (2013)	Yes (2015)	Yes (2015)	Yes (2011)

7.3.1.1 Governance of ex-ante policy evaluation

Denmark has a long history in devising model-based scenario analysis as an instrument to underpin long-term strategies, as is demonstrated in the national renewable energy plans (NREAP) (Ministry of Climate and Energy, 2010) and energy efficiency action plans (NEEAP) (DEA, 2014). However, only since the establishment of the *Climate Change Act* (2014), ex-ante policy evaluation has become more formally embedded within the institutional arrangements for long-term national climate policy planning. This is also reflected in the founding of a Danish Council on Climate Change (CCC), which is responsible for the continuous evaluation of the national movements to meeting national climate objectives and international climate commitments. The Danish CCC may also advise on further needed action in meeting the national 2050 objective (Sørensen et al., 2015).

The *French* long-term climate and energy ambition has been embedded in the *POPE-law* since 2005 (75% GHG emission reductions in 2050 compared to 1990, also denoted as "factor 4"). However, only until more recently, additional specific details on the planned course of development have been formally embedded and described in the *Energy Transition for Green Growth Act* (*Loi de Transition Énergétique pour la Croissance Verte*, LTECV) (Ministry of Ecology Sustainable Development and Energy, 2015a). In preparation of the LTECV, the French national government devised nation-wide stakeholder dialogue sessions to take stock of the visions on long-term development along the "factor 4" objective (DNTE, 2013). Model-based analyses by stakeholders have provided input to these dialogue sessions, and have been found to have influenced the shaping of the LTECV (Argyriou et al., 2016; Mathy et al., 2015; Sartor et al., 2017). As part of the institutional arrangement, the LTECV formalised the establishment of a rotating independent expert committee (*Comité d'experts pour la transition énergétique,* CETE). The CETE is appointed for the course of two years at a time to assess the progress of implementing the national low-carbon strategy (Ministry of Ecology Sustainable Development and Energy, 2015b; n°2015-992, 2015).

In *Germany*, a number of long-term model-based scenario analyses have been commissioned over the years by many different stakeholders, including federal and regional government ministries, environmental NGOs and industry associations (see for an overview Fabra et al. (2015); Hillebrandt et al. (2015)). The recent *Climate plan 2050 (BMUB, 2016a)*, outlining Germany's national low-carbon strategy up to 2050, builds on the knowledge of several of these studies (see e.g. Haller et al. (2015)). The "*Climate Protection Scenario 2050*", also selected in this study, most likely played a crucial role in the planning process, as (1) it reports on emissions of energy use and all other GHG sources and (2) respects several normative restrictions to parallel with existing climate policy and ministerial preferences (such as a nuclear phase-out, the availability of carbon removal technologies for process industry alone and limiting the deployment of biomass via the "access rights concept"). Instead of formalising long-term ambitions into law, Germany has appointed one ministry with the responsibility to develop policies along the communicated long-term ambitions, with established inter-ministerial approval procedures to accredit long-term strategic documents.

For *The Netherlands*, ex-ante policy evaluation has not had a formal role in long-term planning processes and the political debate on long-term national low-carbon pathways has been limited. Although the *Ministry of Economic Affairs* has a history in commissioning model-based policy evaluation assessments of current and planned policies (Daniels and Kruitwagen, 2010; Schoots et al., 2016), these perspectives do not stretch out beyond the 2020-2035 period. Some perspective towards 2050 is offered via indicative (linear) pathways describing the leeway between "extended policy" and "additional policy" in 2023 and a 80% GHG emission reduction goal in 2050 (Ministry of Economic Affairs, 2016). Although national long-term ambitions are not embedded in law, a proposal for a *Climate Change Act* has been submitted to the Dutch parliament in January 2017. The proposed *Climate Change Act* would set binding GHG emission reduction targets for 2030 (55%) and 2050 (95%), while formalising a five-year policy revision cycle and a monitoring authority (Beunderman, 2017).

By enacting the *Climate Change Act* (Climate Change Act 2008 (c. 27), 2008) in 2008, the *United Kingdom* had established an institutional framework that embedded long-term climate ambitions and ex-ante policy evaluation more firmly into law and policy. The *Climate Change Act* required the implementation of a long-term emissions reduction target and a series of carbon budget periods to be legislated by the national administration, following advice from an established Committee on Climate Change (CCC). Hence, to underpin strategic energy and climate policy statements and to quantify the subsequent carbon budgets the UK government has routinely been using model-based scenario analyses. For example, the fourth carbon budget period has been underpinned by six model-based scenario analyses (DECC, 2011), whereas the fifth carbon budget period is supported by four model-based scenario analyses (DECC, 2015).

7.3.1.2 Distribution of ex-ante policy evaluation knowledge and skills

Denmark's modelling skills are spread over a wide variety of institutions partaking in the development of national energy scenarios and models, ranging from universities, research institutions, consultancies and governmental agencies (see e.g. Lund et al. (2011); Mathiesen et al. (2015)). Although the ex-ante policy evaluation studies of the Danish Energy Agency are considered the lead contender in informing Danish policy planning processes, other research groups may be consulted, depending on the focus of each individual analysis.

In *France*, various research institutes and universities have been united in the *French National Alliance for Energy Research Coordination* (ANCRE). ANCRE contains a thematic group that embodies modelling and model-based analysis, which has contributed to the planning of national energy strategies in the past. As such, the ANCRE alliance has mostly been responsible for providing the analytical underpinning for policy planning processes since its establishment, such as during the earlier described nation-wide stakeholder dialogue sessions, the *LTECV* and further outlines of the *LTECV* in policy (ANCRE, 2016; Argyriou et al., 2016).

In *Germany*, model-based analysis is outsourced to external independent bodies which are spread over different scientific institutions (e.g Öko-Institut, Fraunhofer-ISI, DLR German Aerospace Centre), consultancies and academia. The government is in that sense a client, supporting the construct via calls and tenders, allowing for continuity in the field of research regardless of the administration in power. However, through this funding, the government has a certain authority over the direction of the research and modelling being carried out. Although the ambitions presented in the recently published *Climate Plan 2050* is presumably based on a multiplicity of model-based ex-ante policy evaluation studies, they are generally only used for strategic planning.

For t*he Netherlands,* only a limited number of national decarbonisation studies exist that cover the entire energy system. These studies have predominantly been compiled by the Dutch 'planning agencies' (Janssen et al., 2006; Manders and Kool, 2015) or in collaboration with (energy) research institutes as part of broader ex-ante policy evaluation framework looking into the long-term development of the Netherlands (e.g. PBL/ECN (2011)). The national model-based ex-ante evaluation capabilities are currently mostly used to assess the implications of current and planned policies in the near term (up to 2035).

7

In the *United Kingdom*, many of the ex-ante policy evaluation capabilities are held by academic departments, research networks, governmental departments and consultancies (including former government research institutes) (an overview is given in Strachan (2011a); Strachan (2011b)). Only a few models are routinely used for long-term policy planning in the UK, for which the UK MARKAL family of models has provided the underpinning of insights on long-term low-carbon planning from 2003 to 2013 (Committee on Climate Change, 2016; Pye et al., 2015; Strachan, 2011a). The UK MARKAL model has been succeeded by the UK TIMES model, which has been used to inform the setting of the *fifth carbon budget* period (Anandarajah et al., 2013).

7.3.1.3 Stakeholder engagement

Denmark has carried out participatory processes with stakeholders in service of the Danish *Energy Strategy 2050* (2011), exploring long-term perspectives based on multiple seminars mobilising over 1600 participants (Lund and Mathiesen, 2009). Although such processes have built social capacity for long-term national low-carbon depictions, they are mainly used for strategic planning and have not had a formal role in policy.

In *France*, the *National Debate on Energy Transition* (DNTE, 2013) had mobilised various stakeholder groups (academia, industry and NGOs) to develop a framework that clustered multiple existing model-based ex-ante policy evaluation studies into four stylised long-term energy transition scenarios. These four scenarios have been subjected to a multi-criteria assessment in a broader participatory process with stakeholders (a council of 112 members from 7 stakeholders groups), which delivered the identification of a preference order for the considered long-term futures. The first-best option of this participatory process has presumably been adopted in the LTECV (Argyriou et al., 2016; Grandjean et al., 2014).

To gain broader societal consensus for the *Climate Plan 2050*, *Germany* had consulted over 500 stakeholders within federal states, municipalities, industry, interest groups and civil society via multiple participatory methods (respectively via various on-site and online dialogue sessions with stakeholders and the public). The broader (public) stakeholder engagement delivered 97 climate action measures in service of the national 2050 decarbonisation ambitions, which have been collected and published in the "*measurements catalogue*" (BMUB, 2016b). The modelling suite used for the "*Climate Protection Scenario 2050*" supported the (governmental) stakeholder sessions by providing quantitative assessment for the proposed measures (BMUB, 2016b). However, the national dialogues have not led to new comprehensive ex-ante evaluation studies or changes to long-term policy planning.

The Netherlands has no formal embedding of civil society or stakeholders in ex-ante policy evaluation studies toward 2050, which remain mostly a product of the Dutch 'planning agencies'. However, the annual report assessing current and planned policies (Schoots et al., 2016) utilises a broad consortium of modellers, policy analysts and experts to come to independent advice. Separate of ex-ante policy evaluation procedures, the Dutch government had initiated the *Energy Debates* in 2016, inviting multiple governmental representatives, businesses, research institutes and network organisations across the country (representing 72 organisations and 3000 people in total) to share possible solutions to meeting long-term ambitions for 2050. The outcomes of these *Energy Debates* are expected to be used in the formulation of the *Energy Agenda* (Dutch Government, 2016).

The *United Kingdom* draws insights from a wider range of sources than the routinely used model-based evaluation tools, such as expert judgments and other types of analysis (CCC, 2016). For example, some stakeholders have developed their own ex-ante policy evaluation studies, such as the *Energy Technologies Institute*, a public-private partnership maintaining the ESME-model, and the National Grid, supported by its own in-house model. Moreover, in 2010, the UK government launched a public engagement programme to open a public dialogue on how the UK should meet its legally binding targets in 2050. The engagement programme resulted into three local deliberative dialogue sessions utilising the *'2050 Energy Calculator'* tool[9], an online carbon accounting tool developed by the former *Department of Energy and Climate Change* (DECC). Simultaneously, the broader public was engaged via the *'My2050'* serious game interface[10], which engaged over 10.000 participants in using a simplified version of the 2050 calculator. The results have been used to inform policy makers about specific preferences, as well as to inform about patterns in the variation of answers (Comber and Sheikh, 2011).

7.3.2 A quantitative comparison of national ex-ante policy evaluation studies

In this section we compare the actual contents of a selective draw of national representative model-based policy evaluation studies for each Member State. Although the reports written along the selected model-based scenarios vary in style and level of provided quantitative detail, a few common metrics have been identified throughout the studies (respectively greenhouse gas emission reductions, the share of renewable energy in electricity production and total primary energy reductions). These common metrics allow for a cross-comparison between the national studies. To gain additional insights into the considered national developments in a broader European perspective, we portray the representative national model-based scenarios together with the European model-based scenarios (see Figure 7-1).

In relation to total GHG emission reductions, all studies depict an overall similar GHG emission reduction rate for 2030, fluctuating around 50% compared to 1990 levels. The national model-based studies are therefore observed to exceed the EU ambitions (40%) over the near-term, while broadly abiding by the nationally imposed targets. Interestingly, over time the national policy ambitions show to anchor to the EU 2050 ambitions, with a predominant focus on meeting the lower level in the 80%-95% EU 2050 objective. Some exceptions to this rule are found for France (aiming for 75% GHG emission reductions, as described in the LTECV) and Germany (which also explores a pathway towards 95% GHG emission reductions). However, it should be noted that these conclusions can be considered as rather contentious, given our deliberate choice to only select mitigation scenarios aligned with the EU 2050 objective.

We devise the share of renewable energy in electricity production as a first indicator to draw insights on the overall course of development for the power supply sectors for each country. The selective draw in representative national model-based scenario studies yielded a variety of different perspectives on future power system change.

9 http://2050-calculator-tool.decc.gov.uk/

10 http://my2050.decc.gov.uk/

Remarkable for Denmark is that the four included representative national scenarios all reflect similar trajectories towards achieving a full renewable power system by 2035. The study thus represents a discussion on the to-be considered resources towards this objective, describing various combinations of wind power, bioelectricity and hydrogen in the electricity mix. Conversely, the French representative national scenarios show a wide range in possible low-carbon transition routes, all designed around different

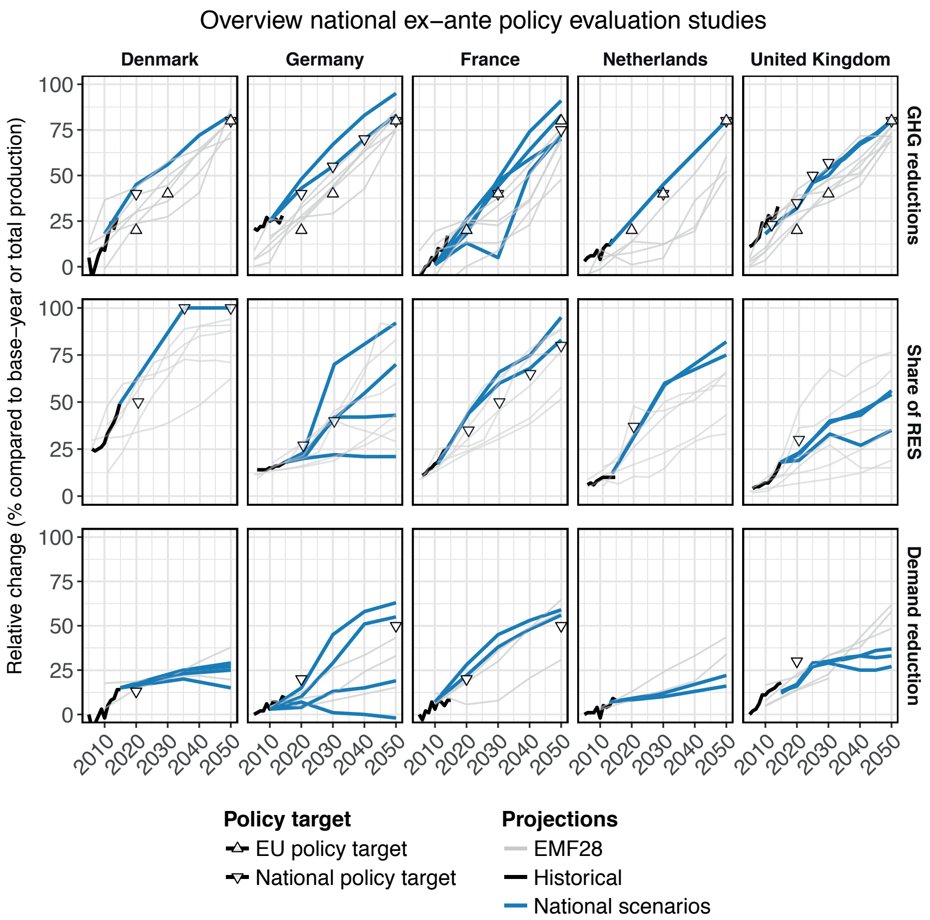


Figure 7-1 - Overview of national low-carbon strategies considered per country, GHG reductions compared to 1990 levels, share of RES represents renewable energy supply in total power generation, demand reduction considers total primary energy demand reduction compared to 2005. Historical references for GHG reductions, renewable energy shares in power production and primary energy reduction retrieved from respectively (Eurostat, 2014a, b, c). Denmark, Germany and Netherlands include GHG emissions of all sectors (excl. LULUCF). Historical reference for France only includes GHG emissions of the energy sector. Historical reference for GHG emissions for the United Kingdom includes all sectors (incl. bunkers), difference with historical data is attributable to differences in accounting and rounding of values. National GHG policy targets for the Netherlands represent the 2030 conditional pledge of 40% (Dutch Government, 2013) and the communicated value for 2050 in the Energy Agenda (Ministry of Economic Affairs, 2016a).

considerations for the current nuclear capital stock. The national model-based scenarios have therefore been used to explore a potential switch from nuclear energy to renewable energy technologies (Grandjean et al., 2014). For Germany, as a result of explicitly exempting technologies such as nuclear and carbon removal (CCS) technologies in power generation for all scenarios, shows to depict a relatively strong orientation towards renewable energy technologies in power production. Regardless of the climate objective assumed, the German scenarios show to favour the deployment of wind over solar power by 2050 (Öko-Institut / Fraunhofer ISI, 2015). The Netherlands reflects a similar development trajectory for renewable energy technologies in power production as Germany, though adding more weight to bioelectricity use, CO_2 removal and demand reduction. The UK scenarios depict a lower renewable energy share in power production over time compared to other countries, partly because the contribution from renewables has been historically one of the lowest in the EU. The depicted scenarios mostly reflect combinations of offshore wind and nuclear power generation.

Large differences are also depicted for the primary energy demand reductions between countries and between scenarios, ranging from no reduction in demand for one of the French scenarios to more than 50% reduction in the French and German scenarios. However, the demand reduction projections may be influenced by (1) the way in which the models are structured (as most techno-economic modelling exercises focus on fuel substitution rather than demand reduction – albeit some explicit assumptions on demand reduction are included in the French scenarios) and (2) a statistical artefact in primary energy accounting (which puts intermittent technologies in a more beneficial position than other decarbonisation technologies). Particularly the latter creates major difficulties in comparing primary energy reductions between scenarios with a stronger focus on renewables energy implementation to scenarios that prescribe a greater role to nuclear and CCS.

The EMF28 scenarios provide alternative national perspectives in the light of broader European developments to meeting long-term the EU 2050 objective. Overall the EMF28 scenarios depict wider ranges of national pathways consistent with the (collective) EU commitment for 2050. One reason for this broader range could be that the representative national scenarios do not (fully) devise the option to make use of the EU internal market, which is the case for the participating models in the EMF28 modelling exercise. As a result of effort sharing principles devised in European modelling frameworks, several national-level projections may thus be higher or lower than currently considered within the national context.

7.4 Discussion

The EU 2030 governance scheme and the long-term national climate and energy plans as requested by the EU Energy Union are intended to provide long-term predictability and certainty to meeting the European objective (European Commission, 2015). However, despite an overall trend of national governments to embrace ambitious policies and legal frameworks, regulatory stability to meeting long-term policy goals provides no guarantee for coherent and consistent policy. This has been relatively recently demonstrated by the UK government, which has shifted the long-term decarbonisation orientation from a focus on all available low-carbon technologies (as was also modelled in an earlier publication of UKERC (2013)) to the prioritisation, at least in the short-term, of nuclear energy and offshore wind. As model-based ex-ante evaluation exercises can only react to, rather than anticipate on, such change in policy, evaluation studies need to be re-evaluated on a frequent basis.

Moreover, the current study finds that national model-based scenario analyses pay little attention to the developments in (or interaction with) other countries. As explicit identification of regional cooperation opportunities are asked under the EU Energy Union governance scheme (EC (2016), art. 11[2]), this would call for further methodological development of model-based ex-ante policy evaluation practices. Considering how all national scenarios assigned a significant role to intermittent electricity production, this may raise questions about how production is balanced to meet demand if not closely attuned with neighbouring countries (EC (2016), art.19[7]). A similar statement can be formulated for biomass imports (EC (2016), art.18[2]), for which varying assumptions about biomass availability have been used in the different national models.

Furthermore, model-based scenario analysis may be considered to have a vital role in pushing (non)governmental stakeholders in thinking beyond conventional solutions (Voinov and Bousquet, 2010). By expanding the focus to other scientific or policy-relevant concepts, rather than limiting the scope to descriptive scenarios bound by national targets, it would allow for broader learning on the (un)available necessary change and future potential among modellers, decision-makers and stakeholders. Particularly in the light of the observed misalignment of national ambitions with global long-term commitments (Kuramochi et al., 2016; UNEP, 2016) and uncertainties in the depicted large-scale deployment of several technologies in model-based scenarios, this would drive further methodological development and improve the usefulness of ex-ante policy evaluation.

Finally, the combination of model-based scenario analysis with broader stakeholder interaction has yielded notable result in France. As recoginised in literature, co-creation via broader stakeholder engagement may allow for mutual learning between modellers and stakeholdes, while simultaneously generating legitimacy and social acceptance for specific transition pathways towards 2050 (Kowarsch, 2016; Voinov and Bousquet, 2010). The French example provides evidence that on-site interaction between modellers and the (stakeholder) audience may have been crucial in achieving this, as approaches that offer no direct feed-back, such as the *My2050* online platform in the UK, have been considered as rather ineffective (Allen and Chatterton, 2013).

7.5 Conclusions

In this study we have elaborated on the ex-ante policy evaluation efforts exercised by five EU Member States. In order to deduct insights on the regulatory and institutional arrangements for ex-ante policy evaluation we have systematically looked at (1) the governance of ex-ante policy evaluation efforts, (2) the distribution of knowledge and skills for ex-ante policy evaluation and (3) the involvement of (public) stakeholders. In a subsequent step we quantitatively compared representative national model-based scenarios and European-wide scenarios to assess their (1) alignment to communicated long-term ambitions and (2) the relative differences among the group of EU countries. We draw the following insights and identify the following good practices:

The regulatory and institutional arrangements for long-term planning, including the use of scenario studies, have been organised very differently in the five included Member States

Effective and durable coordination of long-term ambitions over time is considered to be build on (1) strengthened institutions (interpreted as the embedment of long-term ambitions or intermediate targets into laws and regulations on the national level), (2) expanded resources and capacity and (3) frequent ex-ante policy evaluation efforts (Hovi et al., 2009). The research revealed that the studied five Member States have organised their long-term planning and evaluation practices very differently, resulting into varying levels of policy consistency and transparency for planning towards 2050. In regard to ex-ante policy evaluation, the United Kingdom has institutionalised a reoccurring model-based evaluation cycle over time which allows for adaptive policy planning. Alternatively, France mobilised bottom-up research activities and (stakeholder) collaborations, resulting into greater legitimacy for model-based evaluations and a presumable adoption into policy. Denmark is characterised as a country a clear societal preference for a certain transition pathway, which are then reaffirmed and further deepened with model-based analysis. The German government outsources evaluation practices to independent research organisations, yet uses the outcomes mostly for strategic planning. In the Netherlands ex-ante policy evaluation has concentrated only around a few model-based studies, leading to a low frequency in ex-ante policy evaluation efforts and limited transparency in the considered transition pathway towards 2050.

The closed-system approach in national model-based ex-ante policy evaluation excludes perspective on broader European and global developments

The representative national model-based studies revealed that national studies varied in depth, composition, and embedment into policy design. Interestingly, due to the national resolution, all Member States exposed a rather closed-system approach by focusing only on developments on the national level. As such, all studies paid little attention to the developments in (or interactions with) other countries. Further methodological development in ex-ante policy evaluation processes and cross-border collaboration is therefore recommended as to share and react on considered assumptions on, for example, biomass imports and energy market developments. Further work could also consider broadening the research scope, either via (1) including additional (global) objectives next to national objectives to strengthen the analytical understanding of required transformative change over time and (2) participatory modelling exercises with stakeholders as to draw societal capacity and legitimacy for a specific long-term trajectory towards 2050.

7.5.1 Acknowledgements

The research leading to these results has received funding from the European Union Seventh Framework Programme FP7/2007-2013 under grant agreement n° 603942 (PATHWAYS). JW has received funding from the UK Research Councils for the UK Energy Research Centre (award no. EP/L024756/1).

Chapter 8

Summary and conclusions

8 Summary and conclusions

8.1 Introduction

The 2015 United Nations Climate Change Conference in Paris (COP21) agreed upon limiting global-mean temperature increase to less than 2°C compared to pre-industrial levels and pursue efforts towards limiting temperature increase to 1.5°C. Policymakers that face this climate objective of limiting global warming to well below 2°C are confronted with multiple challenges in policy planning. First of all, the objective covers a long temporal scale, which poses a challenge to the human planning horizon. Secondly, policymakers are confronted with delayed and opaque feedbacks in both the natural and human system, such as long atmospheric lifetimes of some greenhouse gasses or social inertia, which make planning for the future a complex and multi-dimensional challenge. And finally, the response strategies themselves are beset with uncertainty and subjectivity as people have different understandings, opinions and interests in what constitutes the best strategy to limit global warming.

Several fields of research have been developed over the years to structure todays' knowledge about future human system change and to theorise on the directions to which society is heading, or should be heading in the light of the above-mentioned objective to limit global warming. These research fields can broadly be classified into three groups: (1) the historical reference, (2) expert knowledge, and (3) model-based scenario analysis. Of these research fields, model-based scenario analysis is often used to study how specified global sustainability targets, such as limiting global warming, can be achieved within a specified time horizon. One specific type of computational model is frequently used to study the interactions and feedbacks in human and natural systems, combining perspectives of the physical and social sciences in one structured and consistent framework. This model is also known as the *Integrated Assessment Model* (IAM).

IAMs project that, if current trends are to be continued, global mean temperature may be rising by around 3.6°C to 5.2°C at the end of the century compared to the pre-industrial level (assuming a 90% likelihood) (Rogelj et al., 2016a). Alternatively, IAMs can be used to study the development and responses of global systems under changing trends. By specifically linking IAMs to the 2°C climate objective, so-called 2°C pathways are created which describe the course of development under 2°C constraints over time. A multitude of 2°C pathways have been developed by various IAMs across the world, which together provide a perspective on how society could meet the 2°C climate objective. IAMs can, for instance, point at (1) the impact of excluding specific technologies in a mitigation strategy or (2) the impact of policy delays on meeting ambitious targets and the associated costs. The *5th Assessment Report* (AR5) by the

Intergovernmental Panel on Climate Change (IPCC) summarises the available literature on possible response strategies (Clarke et al., 2014).

The 2°C pathways have been helpful in informing negotiators and heads of state during the establishment of the Paris Climate Agreement (G7, 2015; UN, 2015). They, however, have also received criticism. For instance, the 2°C pathways have been criticised on (i) their assumptions on large-scale availability of "negative emissions" technologies (which reflects a greater relative removal of carbon dioxide (CO_2) emissions from, than being emitted into, the atmosphere) (Anderson and Peters, 2016; Fuss et al., 2014), (ii) their assumptions on the scaling behaviour of various technological and non-technological properties (Iyer et al., 2015), (iii) their assumptions about the duration of (techno-economic) system transitions (Höök et al., 2012; Smil, 2008), (iv) ignoring the substantial changes needed on the local level (Grübler, 2004), and (v) not appropriately reproducing social behavioural responses (Li, 2017; Victor, 2015).

Moreover, although IAMs are helpful in informing about key elements of long-term systemic change, insights are generally based on simplified and idealised assumptions on future system change. These simplifications allow to translate real-world complexities into mathematical formulations. While these simplifications are necessary to make model analysis manageable and reproducible, it also means that the diversities and complexities of real-world system processes are not taken into consideration. Therefore, these simplifications may attain results which are not consistent with current practices or with societal expectations (Clarke et al., 2009; Iyer et al., 2015; Riahi et al., 2015). Studies of IAMs may therefore be considered as being more of an exploratory rather than predictive nature.

In the context of attaining the 2°C climate objective it is therefore considered relevant to assess the ability of IAMs to represent future systems change. Moreover, as IAM results have been used in the past to underpin climate policies or international negotiations, it is also of interest to consider how comprehensive integrated assessment models are perceived and devised in policy planning processes.

In this context, the main research question of this thesis is formulated as follows:

What additional insights on the opportunities and challenges of meeting the 2°C climate objective can be obtained from a more detailed analysis and development of model-based scenarios in the context of alternative perspectives?

To answer the main research question several more specific research questions have been formulated:

- ***Research question 1:*** *What insights do regional outcomes of model-based scenarios provide?*
- ***Research question 2:*** *What insights are provided by evaluating 2°C model scenario results to other analytical lenses?*
- ***Research question 3:*** *What insights can be obtained by developing 2°C scenarios based on the information alternative perspectives provide?*
- ***Research question 4:*** *How are integrated assessment models used in policy planning processes towards a low-carbon society?*

This thesis has devised several methodological approaches throughout the chapters (see Table 8-1).

Table 8-1 - Overview of used evaluation method per chapter

		RQ1	RQ2		RQ3		RQ4
ANALYTICAL LENS	**EVALUATION METHOD**	**Ch. 2**	**Ch.3**	**Ch. 4**	**Ch. 5**	**Ch.6**	**Ch.7**
HISTORY	1 Qualitative comparison		•			•	
	2 Quantitative comparison		•			•	
EXPERT	3 Qualitative comparison			•		•	•
	4 Quantitative comparison			•		•	•
IAM	5 Single framework				•	•	
	6 Extended framework	•	•	•	•	•	•

8.2 Summary and conclusions "2°C through different lenses"

8.2.1 Research question 1: What insights do regional outcomes of model-based scenarios provide?

In **Chapter 2** a large ensemble of IAM results have been analysed with respect to the regional results in 2°C scenarios. The IAMs devised in this study have run in a harmonised modelling protocol. Such multi-model inter-comparison studies can be used to identify robust policy-relevant messages or controversies in the collective pool of outcomes. The analysis looked into the systemic trends and responses of five major economies (China, India, Europe, the United States of America and Japan), by analysing the development of CO_2-emission trajectories, annual emission reductions over a selected time frame, the Kaya identity, sectoral emission reductions and the share of power supply technologies within total electricity production. The regional responses have been compared to the global responses to place the modelled systemic changes into perspective. Moreover, the considered 2°C pathways are based on a universal carbon price to emulate the most cost-effective trajectory. This leads to the cheapest reduction strategy globally, but not necessarily to a fair distribution of efforts.

The multi-model comparison highlighted that regional IAM results may vary largely both *within* and *between* IAMs (see Figure 8-1 and 8-2, which reinterpret data from chapter 2). More specifically, the multi-model scenario analysis provided the following insights:

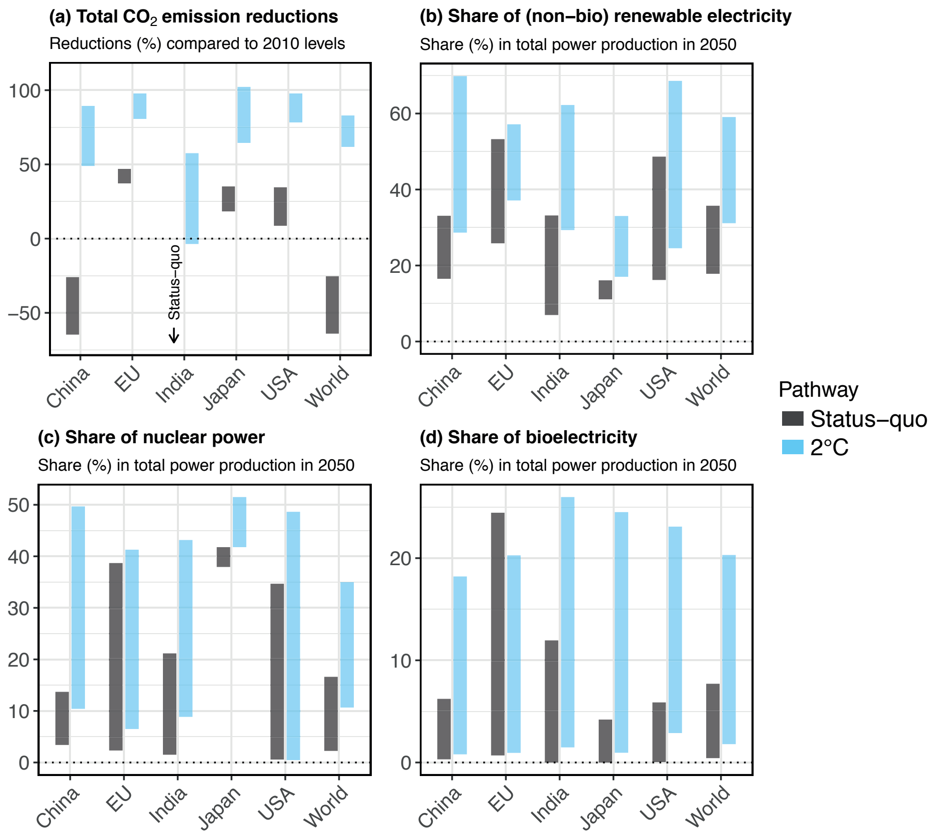


Figure 8-1 (a-d) - Overview of depicted future change by 2050 for major economies (China, India, USA, EU and Japan). The pathway "Status-quo" is denoted as *RefPol* and "2°C" as *RefPol-450* in Chapter 2. Under status-quo assumptions, India is considered to increase its CO_2 emissions substantially (240-410%), which could not be reflected in the current visualisation.

- The result showed that the trends of most of the regional 2°C emission pathways are similar to the trend of the global 2°C emission pathway (e.g. all regions show immediate departure from the current situation under global coordinated action, a greater focus on decarbonisation than on energy efficiency and negative emissions later in the century). Regions with current high or expected rising emissions (such as China, India and the USA) typically show greater mitigation efforts or higher emission reductions than other regions (see Figure 8-1, panel a). The IAMs also reflect differences in regional endowment, such as a shortage of renewable potential for Japan (see Figure 8-1, panel b)

- The 2°C pathways have been found to depend on the type of IAM being used, showing clear signs of a model fingerprint in the depicted decarbonisation strategies. As Figure 8-2 panel b-d depict, several IAMs are more prone to adopting strategies that rely on bioelectricity (IMAGE and to a lesser extent TIAM-ECN), which is connected to a preference for utilising negative emissions. Other IAMs show to privilege the deployment of (non-biomass) renewable power (MESSAGE

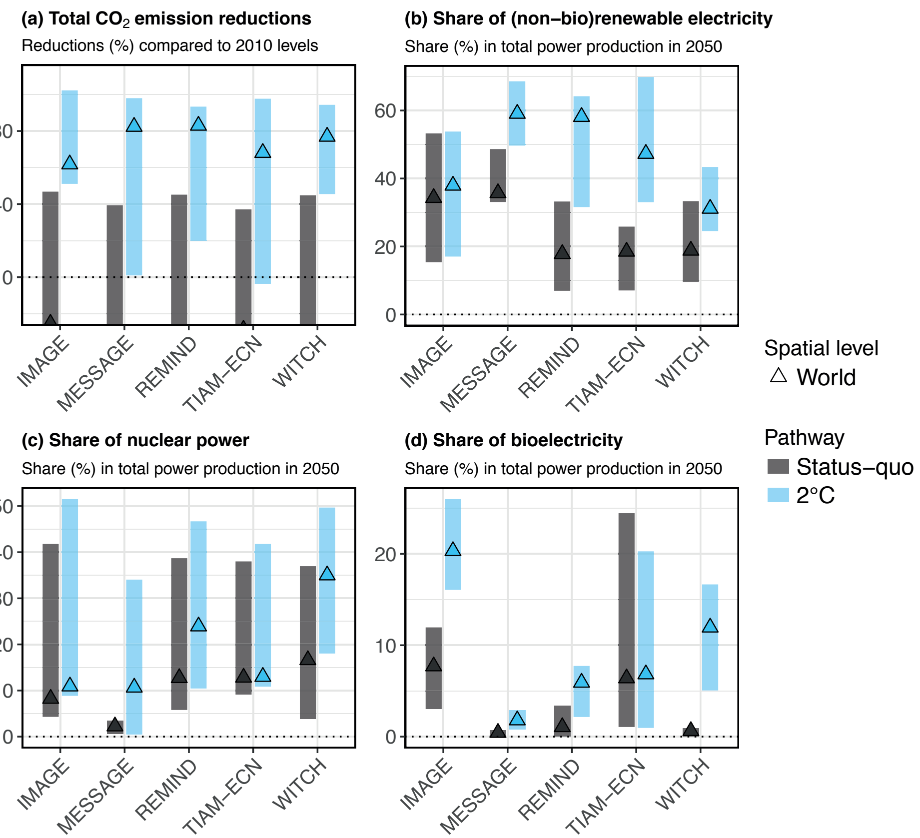


Figure 8-2 (a-d) - Overview of depicted regional future change by 2050 for a select number of IAMs. The range reflects the diversity within five major economies (China, India, USA, EU and Japan). The World outcome represents the weighted average of the total number of world regions accounted for in IAMs (overall greater than the depicted regional range). The total of depicted regions does not reflect the full range of regions accounted for in the World region. The pathway "Status-quo" is denoted as *RefPol* and "2°C" as *RefPol-450* in Chapter 2.

and REMIND). The WITCH model is found to reflect a more diverse portfolio with a less clear technological substitution characterisation, accounting also for energy efficiency strategies to a greater extent.

8.2.2 *Research question 2: What insights are provided by evaluating 2°C model scenario results to results from other analytical lenses?*

Chapter 2 provided various depictions of future change under the 2°C constraint through the lens of IAMs. Although such a multi-model research composition revealed various useful insights on systemic change, further critical appraisal via the use of other analytical lenses may yield additional insights. More specifically, in order to evaluate the rates of change as depicted in 2°C pathways, this thesis compared specific system change metrics of IAMs to their analogous historical counterparts (Chapter 3) and to the results of expert elicitation (Chapter 4).

Chapter 3 used a wide set of indicators describing system change on two different scales (on the system level and technology level) to evaluate how modelled rates of change compare to earlier successful achievement. The analysed system-wide metrics included the average annual CO_2 emission reduction rate, reflecting overall system pressure in 2°C pathways, and the average annual supply-side investments, reflecting societal effort and difficulty in transforming an economy. The analysed technology-related metrics included the average annual capacity additions, reflecting the speed of technological adjustment, and technology diffusion patterns, reflecting the extent and duration of a transition. Both the historical and modelled metrics have been normalised to a representative system growth metric to account for the growth in the system as a whole (defined as total GDP, total investments or total technological capacity in energy supply). Metrics have been compared on face value to earlier achievements and (for technology-related metrics) to the technology with the greatest growth rate in the past (coal-fired power) and the best available rates of change in world regions (for system-wide metrics).

The study revealed that technology-related metrics looking into *absolute* rates of change largely remained in the range of the technology with the greatest growth in the past (coal) for the next decade under 2°C considerations, but increase to unprecedented levels before mid-century. This is mostly due to an overall growth in the system over time. If the metrics are normalised to the total growth in the system, the study finds that the same metrics do not exceed the historical rates. Many technology-related and system changes thus show rates of change beyond their own historical rates over time - but these do not show to exceed the rates of change of the past in relative terms. However, the choice for a normalisation metric is found to be influential to the end result, showing that the choice for a specific normalisation metric could render future rates of change (in)consistent with historical rates.

In **Chapter 4** the IAM outcomes have been systematically compared to projections made by experts in the field of energy supply technology development. These expert projections have been gathered via an expert elicitation protocol specifically designed to acquire comparable and consistent results across a wide range of expertise in energy supply technologies. The analysis looked into wind power, solar power, nuclear power, bioelectricity (with and without coupling to carbon capture and storage (CCS) systems) and fossil fuelled power generation (with and without coupling to CCS systems). Experts have been selected based on their authorship in leading assessment reports, such as the IPCC's *4th Assessment Report* (Sims et al., 2007), the *Global Energy Assessment* (GEA, 2012), the *Special Report of Renewable Energy Sources and Climate Change Mitigation* (Edenhofer et al., 2011) and the *Global Status Report* (REN21, 2014). In total, 39 experts took part in the expert elicitation, including representatives in academia, member-based organisations dedicated to a specific technology, governmental agencies, private sector and intergovernmental organisations. The group of participants therefore included both theoretical and practical knowledge of technological change.

8

All experts have been guided through similar surveys which allowed to consistently test the same type of metric over the various expert groups. The surveys started with an exercise to rank various energy supply technologies in terms of their share in total power supply by 2050. This question has been systematically asked to all experts, which required experts to also assess technologies other than their own field of expertise. The elicitation processes continued with a two-step approach asking experts to formulate a quantitative estimate on expected installed capacity and the expected share in total electricity production. The experts have been asked to provide estimates for both the near-term (2030) and medium-term (2050) under both baseline (status-quo) and 2°C pathway assumptions. In a subsequent step, the elicitation groups were asked to evaluate the average estimate of seven IAMs using the same metrics as before. The experts could assess the presented average IAM values for projections of the near-term (2030) and medium-term (2050), under baseline and 2°C assumptions and evaluate them as "very low", "low", "reasonable", "high" or "very high".

The study showed a relatively high agreement between IAMs and experts on future power system developments under baseline considerations for 2050 (see Figure 8-3, *Baseline* panel). More structural differences in perspective were found for future power system change under 2°C considerations by 2050. These differences particularly emerged in the positioning of the relative contribution of technologies in total power generation (see Figure 8-3, *2 Degrees* panel), showing a wider range of results for both experts and IAMs. Compared to experts, IAMs are found to be more prone to deploying CCS-based power systems and nuclear power by 2050. Conversely, experts assigned a greater role to solar power and bioelectricity in future power generation by 2050. Significant differences in projected magnitudes have been found for a wide range of technologies, with differences found for solar energy, bioelectricity and CCS technologies. Although a significant contribution is considered for CCS technologies over time by the experts, they particularly considered the technology in combination with fossil-fuelled power generation. As a result, the projected contribution of bioelectricity coupled to CCS by IAMs has been considered as optimistic. As IAMs and experts assume a different role and magnitude for bioelectricity in future energy systems, the study revealed a more structural difference in the assumed availability in and economics of bioenergy.

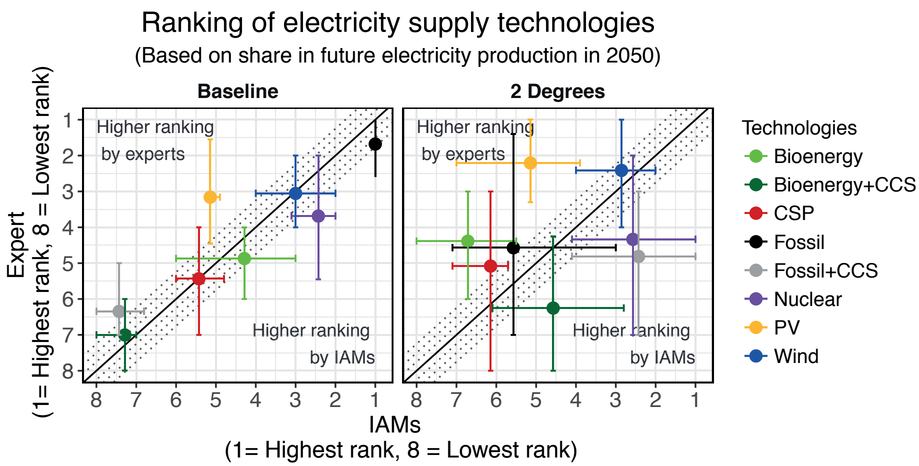


Figure 8-3 - mean ranking of energy technologies in the energy system in 2050 for 39 experts and 7 IAMs. The range provided represents the 15th and 85th percentile of total outcomes. Diagonal line indicates consensus whereas the shaded area represents a range of max 1-point difference

Both chapters provided insights on whether modelled system responses delivered comparable outcomes in the light of different analytical lenses. Although dependent on (1) the type of metric considered and (2) the underlying assumptions on required future change for attaining the 2°C climate objective, the studies show aspects of future transitions that can be considered as robust and other elements that can be considered as more controversial. For example, the projected system change in IAMs is found to remain largely within rates of change as found in the historical evidence (if accounting for growth in the system as a whole and until 2050). However, history can only provide limited guidance on future system change, given different circumstances (no coordinated action towards 2°C) and its reflexive viewpoint (not accounting for future potential). Experts on the other hand are more able to anticipate on (short-term) developments and account for several intricacies not accounted for in the depictions of IAMs, such as has been the case for bioelectricity, nuclear power and CCS. Expert elicitation may thus be useful to detect several market opportunities or uncertainties that are not explicitly represented in IAMs.

8.2.3 Research question 3: What insights do 2°C scenarios developed based on alternative perspectives provide?

Next to testing the robustness of modelled system responses, further insight into future system change has been pursued by looking into areas that are traditionally ignored by IAMs. One of such areas is the considered contribution of behavioural and lifestyle change to attaining the 2°C climate objective. As a result, **chapter 5** presents a relatively simple method to assess the role of lifestyle change by using the *Integrated Model to Assess the Global Environment* (IMAGE). IMAGE has been considered as particularly appropriate for this type of study given its relatively high resolution on a sectoral and service level. Due to this higher resolution, a set of lifestyle change measures for residential energy use, mobility and waste management could be implemented into the IMAGE model. The overall assumed lifestyle changes have been considered as possible within todays' (Western) society and remain in line with evidence found in behavioural and social science literature. The study assumed that the proposed lifestyle changes can emerge in the short term.

The study showed that lifestyle change may lead to substantial CO_2-emission reductions in the residential sector (13%) and the transport sector (35%) compared to the baseline situation in 2050. In a 2°C pathway, lifestyle changes are found to be additional to the existing mitigation strategy. Although overlap is observed with the more commonly implemented technological changes, lifestyle change is found to (1) lower the overall energy demand and (2) reduce the total mitigation costs. Hence, while not being taken into consideration within mainstream IAM literature, this study provided evidence that lifestyle change can contribute to meeting long-term climate objectives.

Further efforts to expand on the notion of social and economic actors and the impact of their behaviour to future system change have been exercised in **chapter 6**. Although earlier work of the IAM community included elements of governance and actor behaviour, they have been commonly addressed via more generic and abstract narrative-based ways (Kriegler et al., 2014a; Nakicenovic et al., 2000; O'Neill et al., 2014). In this study insights on governance and actor behaviour are drawn from socio-technical transition case-studies, which mapped 1) the driving agents of change and 2) their current movements and impact to changing long-term systemic change in various European countries.

The research has been carried out in collaboration with researchers from the socio-technical transition field of research that look into the changes in socio-technical systems over time. These socio-technical system changes are studied by applying the *Multi-Level Perspective* (MLP). In order to allow IAMs and MLP, two fundamentally different disciplinary philosophies, to interact, several operational links have been identified. Given differences in (1) the explanatory style (e.g. narrative-based compared to quantitative assessment), (2) the analytical focus (e.g. emergent and disorderly developments in actor behaviour compared to simplified technologic and economic representations of (energy system) transitions) as well as (3) the type of metric used to describe transitions (qualitative compared to quantitative descriptions of change), these operational links represent shared conceptualisations rather than directly translatable input for IAMs. A key operational link is the *transition narrative*, representing either a considered stylised pattern in MLP or an adoptable narrative in IAMs. Another operational link has been considered for the concepts of *niche momentum* and *system inertia*, representing a notion of breakthrough potential (or momentum) for niche-innovations which could be adopted in IAM scenario assessments.

Via numerous in-depth MLP analyses of niche-innovation developments throughout various countries in Europe, a notional sense of niche momentum was derived based on three analytical dimensions: (1) innovation and markets (techno-economic), (2) actors and social networks (socio-cognitive) and (3) governance and policies over the last 10-15 years. The assessment of the breakthrough potential provided information on whether a transition is eminent or that change in the system is in a much earlier phase. IAM models could respond to these findings by delaying or accelerating a particular future pathway. Moreover, the MLP analyses allowed detecting patterns in terms of the specific actors driving niche developments, which have been reduced to either (1) incumbent actors driving technological substitution practices within the existing regime or (2) new actors that adopt more radical niche-innovations in a broader regime shift. These classifications provided specific context-driven narratives that allowed to design two new transition pathways with evidence-based information on short-term potential change. Both transition pathways have been adopted into the scenario architecture of IAMs and linked to the European climate ambition for 2050.

The modelling exercise found that both transition pathways are compatible with the European climate ambitions for 2050. In the rationale of the considered transition narratives, the study resulted into an experiment on how a long-term objective could be met in the presence or absence of "negative emission" technologies (i.e. bioelectricity coupled to carbon removal systems). In the presence of such technologies, the transition scenario framed around technological substitution methods, resulting into a more rapid decarbonisation of the power sector and sinking surplus carbon emissions via carbon removal and storage technologies. In the absence of such technologies, intermittent renewable energy technologies and demand reductions via behavioural change are notably more important to remain aligned to the European climate ambitions for 2050. Despite assumed low momentum for niche-innovations related to behavioural change in the present, the study underlined the importance of demand-oriented solutions on reducing emissions. However, demand-oriented solutions find only implementation via ad-hoc and assumption-based changes. As a result, transition narratives oriented towards overall broader regime change may find only limited representation in techno-economic assessment by IAMs. The research thus calls for further methodological development to create more informed future (2°C) pathways.

8.2.4 Research question 4: How are integrated assessment models used in policy planning processes towards a low-carbon society?

In the final chapter, the role and contribution of IAMs in providing policy-decision support is further scrutinised. Research by the integrative assessment community has resulted earlier in the adoption of policy targets within the European Union (EU). For example, the EU objective to collectively reduce 80%-95% of total GHG emissions by 2050 is a direct derivative from model-based 2°C conclusions as presented in the *4th Assessment Report* (AR4) by the Intergovernmental Panel on Climate Change (IPCC) (Council of the European Union, 2009; Gupta et al., 2007). Via various policies and regulations, the EU has been stipulating binding and non-binding trajectories of development for its Member States over time to align with the AR4 model-based outcome for 2050. These policies and regulations have been simultaneously adopted and translated into European and national (binding and non-binding) commitments. However, despite notable efforts to monitor the progress of Member States towards aligning to intermediate EU objectives, a more concrete long-term and bottom-up perspective towards 2050 has not yet materialised. This warranted the question on how national planning processes have been shaped to align with long-term ambitions and how model-based scenario analysis may have further contributed to it.

As such, **chapter 7** has analysed the national arrangements for aligning policy and evaluating its consistency with long-term climate objectives in five northwestern European countries (respectively Denmark, France, Germany, the Netherlands and the United Kingdom). The study exercised both qualitative and quantitative evaluation methods to assess the differences between the five European countries. The qualitative evaluation consisted of an assessment of (1) the governance of long-term climate policy, (2) the distribution of knowledge and skills in performing model-based policy evaluation, and (3) the involvement of (public) stakeholders in the planning processes. The quantitative evaluation consisted out of comparative analysis of various representative national scenarios that explore the considered pathways in line with communicated national climate ambitions. These national pathways, produced by IAMs with only a national resolution, have also been compared to projections of IAMs with a broader European perspective.

The study revealed that the national planning processes across the five EU Member States are widely diverse, both in terms of the institutional arrangements for long-term planning and the position and distribution of research bodies performing model-based scenario analysis. Although model-based scenarios have been utilised as an ex-ante policy evaluation tools across the studied countries, their use in national policy planning processes varied in depth and extent. For instance, a binding climate objective in the United Kingdom has ensured a reoccurring model-based evaluation cycle over time which allows for adaptive policy planning. Alternatively, the planning process in France is characterised by a greater involvement and mobilisation of research activities and (stakeholder) collaborations. This approach resulted into greater legitimacy for model-based evaluations and a presumable adoption into policy. Denmark has a preference for a certain transition pathway, which is then reaffirmed and further deepened with model-based analysis. The German government outsources ex-ante policy evaluation studies to national research groups via reoccurring calls and tenders. These policy evaluation studies are mostly used for strategic (policy) planning over time. In the Netherlands ex-ante policy evaluation concentrated only around a few model-based studies, leading to a low frequency in long-term ex-ante policy evaluation efforts and limited transparency in the considered transition pathway towards 2050.

Actual model-based studies revealed that national studies varied in depth, composition, and embedment into policy design. Both exploratory as descriptive scenario techniques have been used, which allowed to deepen or discuss the insight of various policy decisions. However, although all countries have largely adopted the EU-wide 2050 ambitions, the results of the national model-based ex-ante evaluation studies devised a rather closed-system approach. As a result of the national scope and resolution, all model-based ex-ante evaluation studies paid little attention to the developments in, or interaction with, other countries. The coordination of long-term national and EU-wide policy, as well as model-based ex-ante policy evaluation, could benefit from further methodological development in this direction (e.g. by sharing assumptions on, for example, biomass imports and energy market developments).

8.3 Perspective on future challenges and opportunities for 2°C

This thesis has yet so far only discussed the insights on future systems change through the light of each individual analytical lens or in comparison to the integrated assessment model. But what can we learn from the insights combined? By addressing the same question via different research methods (IAMs, historical comparison, expert elicitation and MLP analyses) one can come to better informed insights on the challenges and opportunities associated with aligning to the 2°C climate objective. An example of this is provided in Table 8-2.

Table 8-2 – Synthesis of results provided by various analytical lenses (all results refer result from scenarios aimed at the 2°C target).

	(A)		(B)		(C)
Reference	**Chapter 3**		**Chapter 4**		**Chapter 6**
Spatial reference	**Global**		**Global**		**Europe**
System change Metric	**Normalised average annual capacity addition** [*1] **Best technology=100**		**Rank (importance in tot. power generation)** [*3] **(1 = highest rank) (8 = lowest rank)**		**Niche breakthrough** [*4]
Analytical lens	**IAM (2030-2050)**	**HISTORICAL**[*2]	**IAM (2050)**	**EXPERT (2050)**	**MLP**[*5] **(2015-2016)**
Solar PV	42	18	5.1	2.2	Low/High
Wind	41	37	2.9	1.7	Medium/high
Nuclear	12	25	2.6	4.3	-
Bioenergy w/o CCS	0	7	6.7	4.6	Low/medium
Bioenergy w/ CCS	5	0	4.6	6.3	-
Fossil w/o CCS	1 (coal)	100 (coal)	5.6	4.6	-
Fossil w/ CCS	3 (gas)	0	2.4	4.8	-

[*1] Note 1: The normalised annual capacity growth refers to the growth of capacity per year (GW/yr) divided by the overall size of the economy (total GDP, over the 1980-1012 period) in order to correct for the growth of the energy system. Subsequently, numbers are standardised to the fastest growing technology in the past (coal). The distance to the historical benchmark is used as a measure of total growth potential.

[*2] Note 2: The considered historical period of growth varies per technology, for Solar PV (2003-2013), Wind (2003-2013), Nuclear (1980-1990), Biomass (2005-2011) and Fossil (2003-2012).

[*3] Note 3: The rank metric represents the average value of 39 experts ranking 8 energy supply technologies to importance for the electricity supply system by 2050 under 2°C assumptions (including Fossil, Fossil+CCS, Wind, Solar PV, Solar CSP, Nuclear, PV, Bioenergy, Bioenergy +CCS). For IAMs, the rank represents the average of 7 IAMs, ranking technologies on the relative contribution to total power production.

[*4] Note 4: "Niche momentum" represents the overall qualitative assessment of the breakthrough potential of technological and non-technological niche-innovations on three levels: (1) innovation and market trajectories (techno-economic), (2) actors and social networks (socio-cognitive), and (3) governance and policies over the last 10-15 years.

[*5] Note 5: MLP: Multi-Level Perspective (Socio-technical transition studies)

- **Alignment across the analytical lenses:** All considered analytical lenses have provided confidence that wind power can contribute to future energy system change in line with the 2°C objective. In terms of the historical reference lens, although exceeding expansion rates known to date, the modelled growth rate for wind has been found to not exceed the growth rate as found in historical evidence (A). This provides confidence that the depicted rates of development as provided by IAMs may be attainable given the right circumstances. Secondly, the experts have also provided confidence that the role of wind power in total power supply can be substantial towards 2050 (B), whose expectancies even exceed those of IAMs. Developments towards this direction are already found throughout various countries today (C).

- **Semi-alignment across the analytical lenses**: For solar power, although both IAMs and experts can agree on the importance of this technology in a global mitigation pathway towards 2050, the considered development trajectories over time may vary across the analytical lenses. For example, despite an expected high growth for solar power during the 2030-2050 period within the IAM perspective (A), IAMs are considered to be more reserved about the future deployment and diffusion levels of solar PV in power generation than experts (B). Similar reservations can be found in society today, showing both low to high momentum in adopting solar PV (C).

- **Reflections of uncertainty in the analytical lenses**: For a wide range of technologies the overall outcome is not as clear cut. For example, nuclear power is identified as a possible important technology for future power supply in the view of the IAM lens (B). Given how this technology has seen higher growth rates in the past than modelled for the future (A) this would provide confidence that the depictions of future growth aligned to 2°C may be attainable in the future. However, the experts have articulated a different future outlook (B). Further uncertainty for future development is considered in the deployment of bioelectricity, which needs to be seen in the context of carbon capture and storage (CCS). In IAMs this combination of technologies (referred to as BECCS) is critical given the option of CO_2 removal. This means that IAMs generally do not use biomass in power production if not coupled to CCS systems. The expert lens shows an opposite position towards these technologies, only considering biomass without CCS as a more plausible transition technology (which remains conditional to very specific conditions). Given the lack of an analogous example, history can inherently not provide any confidence for the emergence of a technology like BECCS (A). Similar considerations are found for fossil fuelled power generation (Fossil w/ CCS), having been evaluated as a potential significant contributor to power generation by 2050 by IAMs (B) but receive greater critical appraisal amongst the experts.

Full or semi-alignment in this sense would indicate an opportunity for future system change in line of the 2°C objective. Conversely, more structural differences between the analytical lenses would imply considerable challenges for future system change in terms of technological possibilities, costs and social acceptance. However, the results of this synthesis need to be seen in their context, as (1) the limited availability in metrics only allow to consider power sector developments, (2) a lack of common metrics prevents a direct cross-comparison of analytical perspectives, (3) the limited selection of scenarios, experts or case studies underpin the result only to a limited extent, (4) the use of averages ignores the breadth in possible result and (5) the differences in time periods may have influenced the outcomes (such as the effect of the Fukushima accident in 2011, the Paris Agreement in 2015). Hence, the results of this synthesis may be considered as being more of illustrative nature.

Finally, although the research remains inconclusive on the overall feasibility of attaining the 2°C climate objective, answering the same question via the use of multiple analytical lenses may be considered as a useful means to initiate dialogue between (fundamentally) different disciplinary fields. A broader perspective on future system change allows for critical appraisal of the considered drivers and responses within one's disciplinary field. As such, systematic evaluation of possible future system change in an organised comparative framework may allow for better *framing* and *identification* of future directions of change.

8.4 Future research recommendations

Evaluating future system change is a comprehensive exercise for which multiple focus areas, methods, tools and perspectives are available. Three avenues for further research are to be considered:

- **Expand the scope of evaluation**: In the current work several technology-specific and system-wide metrics have been tested to its comparability with other analytical lenses. However, this generally resulted into a focus on energy system change and the substitution of power supply technologies. Although the energy transition is considered important in the light of attaining the 2°C climate objective, it is recommended to expand the evaluation routines to also consider other metrics and patterns of system change.

- **Expand the scope of integrated assessment:** Insights by IAMs are inherently framed in terms of (1) cost-effectiveness and (2) available potential for substituting technological components to more sustainable alternatives (in both supply and demand sectors). Seeking answers via the use of IAM analysis may thus impose restrictions on how a problem can be perceived, formulated and solved. This underlines a clear need for model-based analysis to include a wider disciplinary perspective and spectrum of value. Supplementing the scope of IAMs may result in more appropriate levels of analysis. New insights may be sought through deeper collaboration with other fields of study, such as social sciences, which may be key in developing our understanding on the implementation, ethics and governance of 2°C pathways.

- **Expand the debate on 2°C pathways:** Chapter 6 and 7 illuminated that more transition pathways may be available than currently accounted for in IAM assessment studies. A broader dialogue with (public) stakeholders may therefore open up considerations of alternative technological possibilities and different 2°C pathways not within todays' scope of assessment. Next to improving the understanding of complex problems, such broader dialogues or (non-scientific) participatory processes can simultaneously be useful methods to create legitimacy and social acceptance for specific future pathways (Kowarsch, 2016; Voinov and Bousquet, 2010). Thus, in order to come to a better solution-oriented assessment of means to attain the 2°C climate objective, a greater engagement of a broader (public) audience is recommended in model-based analyses.

Chapter 9

References

Abrahamse, W., Steg, L., Vlek, C., Rothengatter, T., 2005. A review of intervention studies aimed at household energy conservation. Journal of Environmental Psychology 25, 273-291.

Allen, P., Chatterton, T., 2013. Carbon reduction scenarios for 2050: An explorative analysis of public preferences. Energy Policy 63, 796-808.

Anable, J., Brand, C., Tran, M., Eyre, N., 2012. Modelling transport energy demand: A socio-technical approach. Energy Policy 41, 125-138.

Anadón, L.D., Bosetti, V., Bunn, M., Catenacci, M., Lee, A., 2012. Expert Judgments about RD&D and the Future of Nuclear Energy. Environmental Science & Technology 46, 11497-11504.

Anandarajah, G., Dessens, O., McGlade, C., 2013. Modelling of global energy scenarios under CO2 emissions pathways with TIAM-UCL.

ANCRE, 2016. Activity Report 2015-2016.

Anderson, K., 2015. Duality in climate science. Nature Geosci 8, 898-900.

Anderson, K., Peters, G., 2016. The trouble with negative emissions. Science 354, 182-183.

Argyriou, M., Bataille, C., Colombier, M., Criqui, P., Denis, A., Mathy, S., Sawyer, D., Waisman, H., 2016. The impact of the Deep Decarbonization Pathways Project (DDPP) on domestic decision-making processes – Lessons from three countries, ISSUE BRIEF N°11/16 NOVEMBER 2016 | CLIMATE, Deep Decarbonization Pathways Project - deepdecarbonization.org.

Arrhenius, S., 1896. XXXI. On the influence of carbonic acid in the air upon the temperature of the ground. The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science 41, 237-276.

Baker, E., Chon, H., Keisler, J.M., 2008. Advanced Nuclear Power: Combining Economic Analysis with Expert Elicitations to Inform Climate Policy.

Baker, E., Chon, H., Keisler, J., 2009a. Advanced solar R&D: Combining economic analysis with expert elicitations to inform climate policy. Energy Economics 31, Supplement 1, S37-S49.

Baker, E., Chon, H., Keisler, J., 2009b. Carbon capture and storage: combining economic analysis with expert elicitations to inform climate policy. Climatic Change 96, 379-408.

Baker, E., Bosetti, V., Jenni, K.E., Ricci, E.C., 2014. Facing the Experts: Survey Mode and Expert Elicitation. FEEM Working Paper No. 1.2014. Available at SSRN: https://ssrn.com/abstract=2384487 or http://dx.doi.org/10.2139/ssrn.2384487

Bauer, N., Mouratiadou, I., Luderer, G., Baumstark, L., Brecha, R.J., Edenhofer, O., Kriegler, E., 2013. Global fossil energy markets and climate change mitigation – an analysis with REMIND. Climatic Change, 1-14.

Beck, M., 2017. Modeling climate change impacts at the science-policy boundary. UWSpace.

Bedford, T., Jones, P., Walker, H., 2004. Every little bit helps: Overcoming the challenges to researching, promoting and implementing sustainable lifestyles. Centre of Sustainable Development, University of Westminster, London.

Berkhout, F., Turnheim, B., 2015. Deliverable D4.1 - Tools and procedures for linking three approaches to transition pathways, PATHWAYS project. http://pathways-project.eu/sites/default/files/PATHWAYS_D4%201_Tools%20and%20procedures%2020150528%20FINAL.pdf.

Bernstein, L., Bosch, P., Canziani, O., Chen, Z., Christ, R., Davidson, O., 2007. Climate change 2007: synthesis report. Summary for policymakers, Climate change 2007: synthesis report. Summary for policymakers. IPCC.

Bertram, C., Johnson, N., Luderer, G., Riahi, K., Isaac, M., Eom, J., 2015. Carbon lock-in through capital stock inertia associated with weak near-term climate policies. Technological Forecasting and Social Change 90, Part A, 62-72.

Beunderman, M., 2017. Klimaatwet PvdA-GroenLinks krijgt brede steun, NRC, https://www.nrc.nl/nieuws/2017/01/27/klimaatwet-6435133-a1543351.

BMUB, 2016a. Klimaschutzplan 2050 - Kabinettbeschluss vom 14. November 2016.

BMUB, 2016b. Maßnahmenkatalog - ergebnis des Dialogprozesses zum Klimaschutzplan 2050 der Bundersregierung.

Bosetti, V., Carraro, C., Galeotti, M., Massetti, E., Tavoni, M., 2006. WITCH: A World Induced Technical Change Hybrid Model. The Energy Journal.

Bosetti, V., Carraro, C., Tavoni, M., 2008. Delayed participation of developing countries to climate agreements: should action in the EU and US be postponed?

Bosetti, V., Catenacci, M., Fiorese, G., Verdolini, E., 2012. The future prospect of PV and CSP solar technologies: An expert elicitation survey. Energy Policy 49, 308-317.

Bosetti, V., Anadón, L.D., Baker, E., Reis, L.A., Verdolini, E., 2016. The Future of Energy Technologies: An Overview of Expert Elicitations. GGKP Research Committee on Technology and Innovation Working Paper 01 2016.

Bouwman, A., Kram, T., Klein Goldewijk, K., 2006. Integrated modelling of global environmental change. An overview of IMAGE 2.

Bowen, A., Campiglio, E., Tavoni, M., 2014. A macroeconomic perspective on climate change mitigation: Meeting the financing challenge. Climate Change Economics 5, 1440005.

Cagno, E., Worrell, E., Trianni, A., Pugliese, G., 2013. A novel approach for barriers to industrial energy efficiency. Renewable and Sustainable Energy Reviews 19, 290-308.

Calvin, K., Clarke, L., Krey, V., Blanford, G., Jiang, K., Kainuma, M., Kriegler, E., Luderer, G., Shukla, P.R., 2012. The role of Asia in mitigating climate change: Results from the Asia modeling exercise. Energy Economics 34, Supplement 3, S251-S260.

Calvin, K.V., Wise, M., Klein, D., McCollum, D., Tavoni, M., van der Zwaan, B.C.C., van Vuuren, D.P., 2013. A Multi-Model analysis of the regional and sectoral roles of bioenergy in near -and long-term CO2 emissions reduction. Climate Change Economics 04, 1340014.

CCC, 2016. The fifth carbon budget – The next step towards a low-carbon economy.

Chan, G., Anadon, L.D., Chan, M., Lee, A., 2011. Expert elicitation of cost, performance, and RD&D budgets for coal power with CCS. Energy Procedia 4, 2685-2692.

Chaturvedi, V., Waldhoff, S., Clarke, L., Fujimori, S., 2012. What are the starting points? Evaluating base-year assumptions in the Asian Modeling Exercise. Energy Economics 34, Supplement 3, S261-S271.

Chen, W., Yin, X., Zhang, H., 2016. Towards low carbon development in China: a comparison of national and global models. Climatic Change 136, 95-108.

Clapp, C., Karousakis, K., Buchner, B., Chateau, J., 2009. National and Sectoral GHG Mitigation Potential.

Clarke, L., Lurz, J., Wise, M., Edmonds, J., Kim, S., Smith, S., Pitcher, H., 2007. Model documentation for the minicam climate change science program stabilization scenarios: Ccsp product 2.1 a. Pacific Northwest National Laboratory, PNNL-16735.

Clarke, L., Edmonds, J., Krey, V., Richels, R., Rose, S., Tavoni, M., 2009. International climate policy architectures: Overview of the EMF 22 International Scenarios. Energy Economics 31, Supplement 2, S64-S81.

Clarke, L., Jiang, K., Akimoto, K., Babiker, M., Blanford, G., Fisher-Vanden, K., Hourcade, J.-C., Krey, V., Kriegler, E., Löschel, A., McCollum, D., Paltsev, S., Rose, S., Shukla, P.R., Tavoni, M., van der Zwaan, B.C.C., van Vuuren, D.P., 2014. Assessing Transformation Pathways. In: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S.Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Climate Change Act 2008 (c. 27), 2008. Climate Change Act 2008 - chapter 27.

Comber, N., Sheikh, S., 2011. Evaluation and learning from the 2050 public engagement programme. Office for Public Management.

Committee on Climate Change, 2016. The Fifth Carbon Budget – The next step towards a low-carbon economy.

Council of the European Union, 2009. Brussels European Council 29/30 October 2009 - Presidency conclusions, https://www.consilium.europa.eu/uedocs/cms_data/docs/pressdata/en/ec/110889.pdf.

Csutora, M., 2012. One More Awareness Gap? The Behaviour–Impact Gap Problem. Journal of Consumer Policy 35, 145-163.

Curtright, A.E., Morgan, M.G., Keith, D.W., 2008. Expert Assessments of Future Photovoltaic Technologies. Environmental Science & Technology 42, 9031-9038.

Daioglou, V., van Ruijven, B.J., van Vuuren, D.P., 2012. Model projections for household energy use in developing countries. Energy 37, 601-615.

Daioglou, V., Faaij, A.P., Saygin, D., Patel, M.K., Wicke, B., van Vuuren, D.P., 2013. Energy demand and emissions of the non-energy sector. Energy & Environmental Science 7, 482-498.

Daniels, B., Kruitwagen, S., 2010. Referentieraming energie en emissies 2010-2020.

Danish Energy Agency, 2014. Energy scenarios for 2020, 2035 and 2050.

De Almeida, A., Fonseca, P., Schlomann, B., Feilberg, N., 2011. Characterization of the household electricity consumption in the EU, potential energy savings and specific policy recommendations. Energy and Buildings 43, 1884-1894.

De Boer, H.S.H., van Vuuren, D.D., 2016. Representation of variable renewable energy sources in timer, an aggregated energy system simulation model. Energy Economics.

De Vries, B., Van Vuuren, D., Den Elzen, M., Janssen, M., 2001. Technical Documentation November 2001 The IMAGE Project Department of International Environmental Assessment National Institute of Public Health and the Environment (RIVM) P. O. Box 1 3720 BA Bilthoven The Netherlands.

DEA, 2014. Denmark's National Energy Efficiency Action Plan (NEEAP).

Deane, J.P., Chiodi, A., Gargiulo, M., Ó Gallachóir, B.P., 2012. Soft-linking of a power systems model to an energy systems model. Energy 42, 303-312.

DECC, 2011. Impact Assessment of Fourth Carbon Budget Level.

DECC, 2015. Impact Assessment for the level of the fifth carbon budget.

Den Elzen, M.G., Lucas, P.L., Vuuren, D.P.v., 2008. Regional abatement action and costs under allocation schemes for emission allowances for achieving low CO 2-equivalent concentrations. Climatic change 90, 243-268.

Den Elzen, M.G., van Vuuren, D.P., van Vliet, J., 2010. Postponing emission reductions from 2020 to 2030 increases climate risks and long-term costs. Climatic Change 99, 313-320.

Den Elzen, M.G.J., Hof, A.F., Roelfsema, M., 2011. The emissions gap between the Copenhagen pledges and the 2 °C climate goal: Options for closing and risks that could widen the gap. Global Environmental Change 21, 733-743.

Dietz, T., Gardner, G.T., Gilligan, J., Stern, P.C., Vandenbergh, M.P., 2009. Household actions can provide a behavioral wedge to rapidly reduce US carbon emissions. Proceedings of the National Academy of Sciences 106, 18452-18456.

DNTE, 2013. Quelle trajectoire pour atteindre le mix énergétique en 2025? Quels types de scénarios possibles à horizons 2030 et 2050, dans le respect des engagements climatiques de la France?

Drouet, L., Haurie, A., Labriet, M., Thalmann, P., Vielle, M., Viguier, L., 2005. A Coupled Bottom-Up/Top-Down Model for GHG Abatement Scenarios in the Swiss Housing Sector, in: Loulou, R., Waaub, J.-P., Zaccour, G. (Eds.), Energy and Environment. Springer US, Boston, MA, pp. 27-61.

Dutch Government, 2013. Klimaatagenda: voorkomen, aanpassen en ondernemen, https://www.rijksoverheid.nl/binaries/rijksoverheid/documenten/rapporten/2013/10/04/klimaatagenda-weerbaar-welvarend-en-groen/klimaatagenda.pdf.

Dutch Government, 2016. Einde dialoog in zicht, http://mijnenergie2050.nl/Actueel/563538.aspx.

EC, 2004. Decision No 280/2004/EC of the European Parliament and of the Council of 11 February 2004 concerning a mechanism for monitoring Community greenhouse gas emissions and for implementing the Kyoto Protocol.

EC, 2016. Proposal for a regulation of the European Parliament and the council on the Governance of the Energy Union, amending Directive 94/22/EC, Directive 98/70/EC, Directive 2009/31/EC, Regulation (EC) No 663/2009, Regulation (EC) No 715/2009, Directive 2009/73/EC, Council Directive 2009/119/EC, Directive 2010/31/EU, Directive 2012/27/EU, Directive 2013/30/EU and Council Directive (EU) 2015/652 and repealing Regulation (EU) No 525/2013, http://ec.europa.eu/energy/sites/ener/files/documents/1_en_act_part1_v9_759.pdf.

Edenhofer, O., Pichs-Madruga, R., Sokona, Y., Barros, V., Field, C.B., Zwickel, T., Schlömer, S., Ebi, K., Mastrandrea, M., Mach, K., Von Stechow, C., 2010. IPCC Workshop on Socio-Economic Scenarios, https://www.ipcc.ch/pdf/supporting-material/IPCC_WoSES_Report_final_web.pdf.

Edenhofer, O., Pichs-Madruga, R., Sokona, Y., Seyboth, K., Matschoss, P., Kadner, S., Zwickel, T., Eickemeier, P., Hansen, G., Schlömer, S., von Stechow, C., 2011. IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation. Cambridge University Press, United Kingdom and New York, NY, USA.

Edmonds, J.A., Calvin, K.V., Clarke, L.E., Janetos, A.C., Kim, S.H., Wise, M.A., McJeon, H.C., 2012. Integrated assessment modeling, Climate Change Modeling Methodology. Springer, pp. 169-209.

EEA, 2005. EEA Report 11/2005 — Household Consumption and the Environment.

EEA, 2013. Achieving Energy Efficiency Through Behaviour Change: What Does it Take? Technical report No 5/2013

EEA, 2014. Trends and projections in Europe 2014 - Tracking progress towards Europe's climate and energy targets for 2020.

EEA, 2016. National emissions reported to the UNFCCC and to the EU Greenhouse Gas Monitoring Mechanism.

Elzen, B., Geels, F.W., Hofman, P.S., Green, K., 2004. Socio-technical scenarios as a tool for transition policy: an example from the traffic and transport domain. System Innovation and the Transition to Sustainability: Theory, Evidence and Policy, 251-281.

Eom, J., Edmonds, J., Krey, V., Johnson, N., Longden, T., Luderer, G., Riahi, K., Van Vuuren, D.P., 2015. The impact of near-term climate policy choices on technology and emission transition pathways. Technological Forecasting and Social Change 90, Part A, 73-88.

EPIA, 2014. Global Market Outlook for Photovoltaics 2014–2018". European Photovoltaic Industry Association. http://www.cleanenergybusinesscouncil.com/site/resources/files/reports/EPIA_Global_Market_Outlook_for_Photovoltaics_2014-2018_-_Medium_Res.pdf. European Photovoltaic Industry Association.

European Commission, 2011. Communication from the commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. A Roadmap for moving to a competitive low carbon economy in 2050.

European Commission, 2014. Communication from the commission to the European Parliament, the council, the European Economic and Social Committee, the Committee of the regions and the European Investment bank: A policy framework for climate and energy in the period from 2020 to 2030.

European Commission, 2015. Annex - Guidance to the Member States on the National Energy and Climate plans as part of the Energy Union Governance to the Communication from the commission to the European Parliament, the council, the European Economic and Social Committee, the Committee of the regions and the European Investment bank: - State of the Energy Union, COM(2015) 572 final.

European Commission, 2016. Proposal for a regulation of the European Parliament and of the Council on the Governance of the Energy Union COM(2016) 759 final.

European Union, 2009a. Decision No 406/2009/EC of the European Parliament and of the Council of 23 April 2009 on the effort of Member States to reduce their greenhouse gas emissions to meet the Community's greenhouse gas emission reduction commitments up to 2020.

European Union, 2009b. Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC.

European Union, 2009c. Directive 2009/29/EC of the European Parliament and of the Council of 23 April 2009 amending Directive 2003/87/EC so as to improve and extend the greenhouse gas emission allowance trading scheme of the Community.

European Union, 2012. Consolidated version of the treaty on the Functioning of the European Union, Official Journal C 326, p. 47–390.

European Union, 2013. Regulation (EU) No 525/2013 of the European Parliament and of the Council of 21 May 2013 on a mechanism for monitoring and reporting greenhouse gas emissions and for reporting other information at national and Union level relevant to climate change and repealing Decision No 280/2004/EC Text with EEA relevance. Official Journal of the European Union, L 165, 18 June 2013.

Eurostat, 2014a. Electricity generated from renewable sources - % of gross electricity consumption, http://ec.europa.eu/eurostat/tgm/table.do?tab=table&init=1&plugin=1&language=en&pcode=tsdcc330.

Eurostat, 2014b. Greenhouse gas emissions by sector (source: EEA) - million tonnes of CO2 equivalent, http://ec.europa.eu/eurostat/tgm/table.do?tab=table&init=1&language=en&pcode=tsdcc210&plugin=1.

Eurostat, 2014c. Primary production of energy by resource - 1 000 tonnes of oil equivalent, http://ec.europa.eu/eurostat/tgm/table.do?tab=table&init=1&language=en&pcode=ten00076&plugin=1.

Fabra, N., Matthes, F.C., Newbery, D., Colombier, M., Mathieu, M., Rüdinger, A., 2015. The energy transition in Europe: Initial lessons from Germany, the UK and France. [online] [accessed 03-02-2017] http://www.cerre.eu/sites/cerre/files/151006_CERREStudy_EnergyTransition_Final.pdf.

Fiorese, G., Catenacci, M., Bosetti, V., Verdolini, E., 2014. The power of biomass: Experts disclose the potential for success of bioenergy technologies. Energy Policy 65, 94-114.

Fisher, B.S., Nakicenovic, N., Alfsen, K., Corfee-Morlot, J., Chesnaye, F., Hourcade, J.-C., Jiang, K., Kainuma, M., La Rovere, E., Matysek, A., 2007. Issues related to mitigation in the long term context. Cambridge University Press.

Fouquet, R., Pearson, P.J.G., 2012. Past and prospective energy transitions: Insights from history. Energy Policy 50, 1-7.

Fujimori, S., Dai, H., Masui, T., Matsuoka, Y., 2016. Global energy model hindcasting. Energy 114, 293-301.

Fuss, S., Canadell, J.G., Peters, G.P., Tavoni, M., Andrew, R.M., Ciais, P., Jackson, R.B., Jones, C.D., Kraxner, F., Nakicenovic, N., Le Quere, C., Raupach, M.R., Sharifi, A., Smith, P., Yamagata, Y., 2014. Betting on negative emissions. Nature Clim. Change 4, 850-853.

G7, 2015. Leaders declaration G7 summit - Think Ahead, Act Together, 7-8 June 2015, Schloss Elmau.

Gardner, G.T., Stern, P.C., 2008. The short list: The most effective actions US households can take to curb climate change. Environment: science and policy for sustainable development 50, 12-25.

Garg, A., Shukla, P., 2009. Coal and energy security for India: role of carbon dioxide (CO 2) capture and storage (CCS). Energy 34, 1032-1041.

Gatersleben, B., Steg, L., Vlek, C., 2002. Measurement and determinants of environmentally significant consumer behavior. Environment and behavior 34, 335-362.

GEA, 2012. Global Energy Assessment - Toward a Sustainable Future, Cambridge University Press, Cambridge, UK and New York, NY, USA and the International Institute for Applied Systems Analysis, Laxenburg, Austria.

Geden, O., 2015. Policy: Climate advisers must maintain integrity.

Geels, F.W., 2002. Technological transitions as evolutionary reconfiguration processes: a multi-level perspective and a case-study. Research Policy 31, 1257-1274.

Geels, F.W., 2005. Processes and patterns in transitions and system innovations: refining the co-evolutionary multi-level perspective. Technological forecasting and social change 72, 681-696.

Geels, F.W., Schot, J., 2007. Typology of sociotechnical transition pathways. Research Policy 36, 399-417.

Geels, F.W., McMeekin, A., Hodson, M., 2015. Country report 2: Green niche-innovations in the UK electricity system.

Geels, F.W., Berkhout, F., van Vuuren, D.P., 2016. Bridging analytical approaches for low-carbon transitions. Nature Clim. Change advance online publication.

Geppert, J., Stamminger, R., 2010. Do consumers act in a sustainable way using their refrigerator? The influence of consumer real life behaviour on the energy consumption of cooling appliances. International Journal of Consumer Studies 34, 219-227.

Girod, B., van Vuuren, D.P., Deetman, S., 2012. Global travel within the 2 C climate target. Energy Policy 45, 152-166.

Girod, B., van Vuuren, D.P., de Vries, B., 2013. Influence of travel behavior on global CO2 emissions. Transportation Research Part A: Policy and Practice 50, 183-197.

Global Wind Energy Council, 2015. Global status of wind power in 2015.

Goodall, C., 2010. How to live a low-carbon life: the individual's guide to stopping climate change. Routledge.

Grandjean, A., Blanchet, E., Finidori, E., 2014. Étude des 4 tranjectoires du DNTE - Une vision pédagogique des 4 trajectoires étudiées dans le cadre de débat national sur la transition energétique.

Grübler, A., Nakićenović, N., Victor, D.G., 1999. Dynamics of energy technologies and global change. Energy Policy 27, 247-280.

Grübler, A., 2004. Transitions in energy use. Encyclopedia of energy 6, 163-177.

Grübler, A., 2012. Energy transitions research: Insights and cautionary tales. Energy Policy 50, 8-16.

Gupta, S., Tirpak, D.A., Burger, N., Gupta, J., Höhne, N., Boncheva, A.I., Kanoan, G.M., Kolstad, C., Kruger, J.A., Michaelowa, A., Murase, S., Pershing, J., Saijo, T., Sari, A., 2007. Policies, Instruments and Co-operative Arrangements, In Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [B. Metz, O.R. Davidson, P.R. Bosch, R. Dave, L.A. Meyer (eds)], Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. .

Gutowski, T., Taplett, A., Allen, A., Banzaert, A., Cirinciore, R., Cleaver, C., Figueredo, S., Fredholm, S., Gallant, B., Jones, A., 2008. Environmental life style analysis (ELSA), Electronics and the Environment, 2008. ISEE 2008. IEEE International Symposium on. IEEE, pp. 1-5.

GWEC, 2014. Global Wind Statistics 2013. Global Wind Energy Council. http://www.gwec.net/wp-content/uploads/2014/02/GWEC-PRstats-2013_EN.pdf.

Hallding, K., 2011. Together alone: BASIC countries and the climate change conundrum. Nordic Council of Ministers.

Haller, M., Repenning, J., Vogel, M., Schlomanhn, B., Reuter, M., Jochem, E., Reitze, F., Schon, M., Toro, F., 2015. Überblick über vorliegende Szenarienarbeiten für den Klimaschutz in Deutschland bis 2050, Öko-Institut e.V., Fraunhofer Institut für System- und Innovationsforschung, IREES GmbH (Institut für Ressourceneffizienz und Energiestrategien).

Harding, M., Rapson, D., 2013. Does absolution promote sin? The conservationist's dilemma, University of California, Davis Working Paper.

Hillebrandt, K., Samadi, S., Fischedick, M., Eckstein, S., Höller, S., Janßen, T., Kamps, K., Krüger, C., Lechtenböhmer, S., Nigge, G., Pastowski, A., Sellke, P., 2015. Pathways to deep decarbonization in Germany. SDSN - IDDRI.

Hodson, M., Geels, F., McMeekin, A., 2014. Country report 6: Green niche-innovations in the UK mobility system.

Hof, A.F., Van Sluisveld, M.A.E., Deetman, S., Van Vuuren, D.P., 2013. Feasibility of Transitions in 2 Degree Scenarios, Scenario report 2: workshop report.

Hong, L., Zhou, N., Fridley, D., Raczkowski, C., 2013. Assessment of China's renewable energy contribution during the 12th Five Year Plan. Energy Policy 62, 1533-1543.

Höök, M., Li, J., Johansson, K., Snowden, S., 2012. Growth Rates of Global Energy Systems and Future Outlooks. Natural Resources Research 21, 23-41.

Hourcade, J.-C., Jaccard, M., Bataille, C., Ghersi, F., 2006. Hybrid Modeling: New Answers to Old Challenges Introduction to the Special Issue of" The Energy Journal". The Energy Journal, 1-11.

Hovi, J., Sprinz, D.F., Underdal, A., 2009. Implementing long-term climate policy: Time inconsistency, domestic politics, international anarchy. Global Environmental Politics 9, 20-39.

IEA, 2004. Oil Crises & Climate Challenges — 30 Years of Energy Use in IEA Countries.

IEA, 2008. Worldwide Trends in Energy Use and Efficiency.

IEA, 2011. World Energy Outlook.

IEA, 2012. World Energy Outlook.

IEA, 2013. Energy policies of IEA: Germany.

IEA, 2014. Energy policies of IEA country: The Netherlands.

IEA, 2014a. World Energy Investment Outlook 2014 http://https//www.iea.org/publications/freepublications/publication/WEIO2014.pdf.

IPCC, 2007. Summary for Policymakers. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M.Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

IPCC, 2014a. AR5 Scenario Database, in: III, W.G. (Ed.), https://tntcat.iiasa.ac.at/AR5DB.

IPCC, 2014b. Climate Change 2014 - Synthesis Report. Intergovernmental panel on Climate Change.

IPCC, 2014c. Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 151 pp.

IPCC, 2014d. Summary for Policymakers. In: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

IPCC, 2017. IPCC Factsheet: What is the IPCC?, http://www.ipcc.ch/news_and_events/docs/factsheets/FS_what_ipcc.pdf.

IRENA, 2016. Letting in the light - how solar photovoltaics will revolutionise the electricity system.

Isaac, M., Van Vuuren, D.P., 2009. Modeling global residential sector energy demand for heating and air conditioning in the context of climate change. Energy Policy 37, 507-521.

Iyer, G., Hultman, N., Eom, J., McJeon, H., Patel, P., Clarke, L., 2015. Diffusion of low-carbon technologies and the feasibility of long-term climate targets. Technological Forecasting and Social Change 90, Part A, 103-118.

Jakeman, A.J., Letcher, R.A., Norton, J.P., 2006. Ten iterative steps in development and evaluation of environmental models. Environmental Modelling & Software 21, 602-614.

Janssen, L.H.J.M., Okkes, V.R., Schuur, J., 2006. Welvaart en Leefomgeving: een scenariostudie voor Nederland in 2040, Centraal Planbureau, Milieu -en Natuurplanbureau en Ruimtelijk Planbureau.

Jebaraj, S., Iniyan, S., 2006. A review of energy models. Renewable and Sustainable Energy Reviews 10, 281-311.

Jenni, K.E., Baker, E.D., Nemet, G.F., 2013. Expert elicitations of energy penalties for carbon capture technologies. International Journal of Greenhouse Gas Control 12, 136-145.

Johansson, D.J., Lucas, P.L., Weitzel, M., Ahlgren, E.O., Bazaz, A., Chen, W., den Elzen, M.G., Ghosh, J., Grahn, M., Liang, Q.-M., 2012. Multi-model analyses of the economic and energy implications for China and India in a post-Kyoto climate regime. Kiel Working Paper.

Jordan, A.J., Liefferink, D., 2004. Environmental policy in Europe: the Europeanization of national environmental policy. Routledge.

Kainuma, M., Matsuoka, Y., Morita, T., Masui, T., Takahashi, K., 2004. Analysis of global warming stabilization scenarios: the Asian-Pacific Integrated Model. Energy Economics 26, 709-719.

Kainuma, M., Matsuoka, Y., Morita, T., 2011. Climate policy assessment: Asia-Pacific integrated modeling. Springer Science & Business Media.

Kaya, Y., 1990. Impact of carbon dioxide emission control on GNP growth: interpretation of proposed scenarios. IPCC energy and industry subgroup, response strategies working group, Paris 76.

Keeney, R.L., von Winterfeldt, D., 1991. Eliciting probabilities from experts in complex technical problems. IEEE Transactions on Engineering Management 38, 191-201.

Keppo, I., Zwaan, B., 2011. The Impact of Uncertainty in Climate Targets and CO2 Storage Availability on Long-Term Emissions Abatement. Environmental Modeling & Assessment 17, 177-191.

Knopf, B., Chen, Y.-H.H., De Cian, E., Förster, H., Kanudia, A., Karkatsouli, I., Keppo, I., Koljonen, T., Schumacher, K., Van Vuuren, D.P., 2013. Beyond 2020—Strategies and costs for transforming the European energy system. Climate Change Economics 4, 1340001.

Kowarsch, M., 2016. Elements of a Guideline for Future Integrated Economic Assessments of the IPCC, A Pragmatist Orientation for the Social Sciences in Climate Policy: How to Make Integrated Economic Assessments Serve Society. Springer International Publishing, Cham, pp. 275-299.

Kramer, G.J., Haigh, M., 2009. No quick switch to low-carbon energy. Nature 462, 568-569.

Kriegler, E., Tavoni, M., Aboumahboub, T., Luderer, G., Calvin, K.V., Demaere, G., Krey, V., Riahi, K., Rösler, H., Schaeffer, M., van Vuuren, D.P., 2013. What does the 2°C target imply for a global climate agreement in 2020? The LIMITS study on Durban platform scenarios. Climate Change Economics 04, 1340008.

Kriegler, E., Edmonds, J., Hallegatte, S., Ebi, K.L., Kram, T., Riahi, K., Winkler, H., Van Vuuren, D.P., 2014a. A new scenario framework for climate change research: the concept of shared climate policy assumptions. Climatic Change 122, 401-414.

Kriegler, E., Weyant, J.P., Blanford, G.J., Krey, V., Clarke, L., Edmonds, J., Fawcett, A., Luderer, G., Riahi, K., Richels, R., Rose, S.K., Tavoni, M., van Vuuren, D.P., 2014b. The role of technology for achieving climate policy objectives: overview of the EMF 27 study on global technology and climate policy strategies. Climatic Change 123, 353-367.

Kriegler, E., Petermann, N., Krey, V., Schwanitz, V.J., Luderer, G., Ashina, S., Bosetti, V., Eom, J., Kitous, A., Méjean, A., Paroussos, L., Sano, F., Turton, H., Wilson, C., Van Vuuren, D.P., 2015. Diagnostic indicators for integrated assessment models of climate policy. Technological Forecasting and Social Change 90, Part A, 45-61.

Kruger, T., Geden, O., Rayner, S., 2016. Abandon hype in climate models, The Guardian.

Kuramochi, T., Höhne, N., Gonzales-Zuñiga, S., Hans, F., Sterl, S., Hagemann, M., Hernandez Legaria, E., den Elzen, M., Roelfsema, M., van Soest, H., Forsell, N., Turkovska, O., 2016. Greenhouse gas mitigation

9

scenarios for major emitting countries. Analysis of current climate policies and mitigation pledges.

Lawrence Berkeley National Laboratory, 2013. Standby power summary table, http://standby.lbl.gov/summary-table.html.

Li, F.G.N., 2017. Actors behaving badly: Exploring the modelling of non-optimal behaviour in energy transitions. Energy Strategy Reviews 15, 57-71.

Lipscy, P.Y., Schipper, L., 2013. Energy efficiency in the Japanese transport sector. Energy Policy 56, 248-258.

Loftus, P.J., Cohen, A.M., Long, J.C.S., Jenkins, J.D., 2015. A critical review of global decarbonization scenarios: what do they tell us about feasibility? Wiley Interdisciplinary Reviews: Climate Change 6, 93-112.

Lucas, P.L., van Vuuren, D.P., Olivier, J.G., Den Elzen, M.G., 2007. Long-term reduction potential of non-CO 2 greenhouse gases. Environmental Science & Policy 10, 85-103.

Lucas, P.L., Shukla, P., Chen, W., van Ruijven, B.J., Dhar, S., den Elzen, M.G., van Vuuren, D.P., 2013. Implications of the international reduction pledges on long-term energy system changes and costs in China and India. Energy Policy 63, 1032-1041.

Lucon, O., Ürge-Vorsatz, D., Ahmed, A.Z., Akbari, H., Bertoldi, P., Cabeza, L., Eyre, N., Gadgil, A., Harvey, L., Jiang, Y., 2014. Buildings. Working Group III contribution to the IPCC 5th assessment report, climate change 2014: mitigation of climate change.

Luderer, G., Pietzcker, R.C., Kriegler, E., Haller, M., Bauer, N., 2012. Asia's role in mitigating climate change: A technology and sector specific analysis with ReMIND-R. Energy Economics 34, S378-S390.

Luderer, G., Leimbach, M., Bauer, N., Kriegler, E., 2013. Description of the REMIND model (Version 1.5).

Luderer, G., Krey, V., Calvin, K., Merrick, J., Mima, S., Pietzcker, R., Van Vliet, J., Wada, K., 2014. The role of renewable energy in climate stabilization: results from the EMF27 scenarios. Climatic Change 123, 427-441.

Luderer, G., Bertram, C., Calvin, K., De Cian, E., Kriegler, E., 2016. Implications of weak near-term climate policies on long-term mitigation pathways. Climatic Change 136, 127-140.

Lund, H., Mathiesen, B.V., 2009. Energy system analysis of 100% renewable energy systems—The case of Denmark in years 2030 and 2050. Energy 34, 524-531.

Lund, H., Hvelplund, F., Mathiesen, B.V., Ostergaard, P.A., Christensen, P., Connolly, D., Schaltz, E., Pollay, J.R., Nielsen, M.P., Felby, C., Bentsen, N.S., Meyer, N.I., Tonini, D., Astrup, T., Heussen, K., Morthorst, P.E., Andersen, F.M., Münster, M., Hansen, L.P., Wenzel, H., Hamelin, L., Munksgaard, J., Karnoe, P., Lind, M., 2011. Coherent Energy and Environmental System Analysis.

Macknick, J., 2011. Energy and CO_2 emission data uncertainties. Carbon Management 2, 189-205.

Madlener, R., Alcott, B., 2009. Energy rebound and economic growth: A review of the main issues and research needs. Energy 34, 370-376.

Manders, T., Kool, C., 2015. Welvaart en leefomgeving 2015: Nederland in 2030 en 2050: twee referentiescenario's, Welvaart en leefomgeving 2015, Den Haag: Planbureau voor de Leefomgeving/Centraal Planbureau.

Markard, J., Raven, R., Truffer, B., 2012. Sustainability transitions: An emerging field of research and its prospects. Research Policy 41, 955-967.

Marquard, J.L., Robinson, S.M., 2008. Reducing Perceptual and Cognitive Challenges in Making Decisions with Models, in: Kugler, T., Smith, J.C., Connolly, T., Son, Y.-J. (Eds.), Decision Modeling and Behavior in Complex and Uncertain Environments. Springer New York, New York, NY, pp. 33-55.

Martin, T.G., Burgman, M.A., Fidler, F., Kuhnert, P.M., Low-Choy, S., McBride, M., Mengersen, K., 2012. Eliciting Expert Knowledge in Conservation Science Obtención de Conocimiento de Expertos en Ciencia de la Conservación. Conservation Biology 26, 29-38.

Mathiesen, B.V., Lund, H., Hansen, K., Skov, I.R., Djørup, S.R., Nielsen, S., Sorknæs, P., Thellufsen, J.Z., Grundahl, L., Lund, R.S., Drysdale, D.W., Connolly, D., Østergaard, P.A., 2015. IDA's Energy Vision 2050: A Smart Energy System strategy for 100% renewable Denmark.

Mathy, S., Criqui, P., Hourcade, J.C., 2015. Pathways to Deep Decarbonization in 2050 in France. The French report of the Deep Decarbonization Pathways Project of the Sustainable Development Solutions Network and the Institute for Sustainable Development and International Relations.

Matthijsen, J., Aalbers, R., van den Wijngaart, R., 2015. Toekomstverkenning Welvaart en Leefomgeving - Cahier Klimaat en Energie, CPB/PBL.

McCollum, D., Nagai, Y., Riahi, K., Marangoni, G., Calvin, K., Pietzcker, R., Van Vliet, J., van der Zwaan, B., 2013. Energy investments under climate policy: a comparison of global models. Climate Change Economics 4, 1340010.

McCollum, D.L., Wilson, C., Pettifor, H., Ramea, K., Krey, V., Riahi, K., Bertram, C., Lin, Z., Edelenbosch, O.Y., Fujisawa, S., 2016. Improving the behavioral realism of global integrated assessment models: An application to consumers' vehicle choices. Transportation Research Part D: Transport and Environment.

McGlade, C., Pye, S., Watson, J., Bradshaw, M., Ekins, P., 2016. The future role of natural gas in the UK, Research Report. London: UK Energy Research Centre.

Meinshausen, M., Meinshausen, N., Hare, W., Raper, S.C.B., Frieler, K., Knutti, R., Frame, D.J., Allen, M.R., 2009. Greenhouse-gas emission targets for limiting global warming to 2[thinsp][deg]C. Nature 458, 1158-1162.

Melton, N., Axsen, J., Sperling, D., 2016. Moving beyond alternative fuel hype to decarbonize transportation. Nature Energy 1, 16013.

Messner, S., Strubegger, M., 1995. User's guide for MESSAGE III. International Institute for Applied Systems Analysis (IIASA).

Metayer, M., Breyer, C., Fell, H.J., 2015. The projections for the future and quality in the past of the World Energy Outlook for solar PV and other renewable energy technologies, Energy Watch Group.

Metz, B., Davidson, O., Bosch, P., Dave, R., Meyer, L., 2007. Climate Change 2007: Mitigation of Climate Change, Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, ISBN.

Ministry of Climate and Energy, 2010. National Action Plan - For renewable energy in Denmark.

Ministry of Ecology Sustainable Development and Energy, 2015a. Energy transition for the green growth act.

Ministry of Ecology Sustainable Development and Energy, 2015b. Stratégie Nationale Bas-Carbone.

Ministry of Economic Affairs, 2016. Energieagenda, https://www.rijksoverheid.nl/documenten/rapporten/2016/12/07/ea.

Morgan, M.G., 2014. Use (and abuse) of expert elicitation in support of decision making for public policy. Proceedings of the National Academy of Sciences 111, 7176-7184.

9

Moss, R.H., Edmonds, J.A., Hibbard, K.A., Manning, M.R., Rose, S.K., Van Vuuren, D.P., Carter, T.R., Emori, S., Kainuma, M., Kram, T., 2010. The next generation of scenarios for climate change research and assessment. Nature 463, 747-756.

n°2015-992, 2015. Article L145-1: Chapter V: The Expert Committee on the Energy Transition.

Nakicenovic, N., Alcamo, J., Davis, G., de Vries, B., Fenhann, J., Gaffin, S., Gregory, K., Grübler, A., Jung, T.Y., Kram, T., Emilio la Rovere, E., Michaelis, L., Mori, S., Morita, T., Pepper, W., Pitcher, H., Price, L., Riahi, K., Roehrl, A., Rogner, H., Sankovski, A., Schlesinger, M., Shukla, P., Smith, S., Swart, R., van Rooyen, S., Victor, N., Dadi, Z., 2000. IPCC Special Reports: Special Report on emissions scenarios. Cambridge University Press, Cambridge, UK.

Napp, T., Gambhir, A., Thomas, R., Hawkes, A., Bernie, D., Lowe, J., 2015. Exploring the feasibility of low-carbon scenarios using historical energy transitions analysis.

National Policy Unit, 2013. Options for Energy and the Environment The Energy and Environment Council Decision on June 29, 2012, https://s3-ap-northeast-1.amazonaws.com/sentakushi01/public/pdf/Outline_English.pdf.

Nemet, G.F., Baker, E., Jenni, K.E., 2013. Modeling the future costs of carbon capture using experts' elicited probabilities under policy scenarios. Energy 56, 218-228.

Nilsson, M., Jordan, A., Turnpenny, J., Hertin, J., Nykvist, B., Russel, D., 2008. The use and non-use of policy appraisal tools in public policy making: an analysis of three European countries and the European Union. Policy Sciences 41, 335-355.

Nordhaus, W.D., 1992. The'dice'model: Background and structure of a dynamic integrated climate-economy model of the economics of global warming. Cowles Foundation for Research in Economics, Yale University.

Notenboom, J., Boot, P., Koelemeijer, R., Ros, J., 2012. Climate and energy roadmaps towards 2050 in north-west Europe.

Nykvist, B., Dzebo, A., 2015. Country report 3: Green niche-innovations in the Swedish heat system.

O'Neill, B.C., Kriegler, E., Riahi, K., Ebi, K.L., Hallegatte, S., Carter, T.R., Mathur, R., van Vuuren, D.P., 2014. A new scenario framework for climate change research: the concept of shared socioeconomic pathways. Climatic Change 122, 387-400.

OECD, 2008. Household Behaviour and the Environment — Reviewing the Evidence.

OECD, 2010a. Climate Change. OECD Publishing, http://www.oecd-ilibrary.org/environment/oecd-environmental-performance-reviews-japan-2010/climate-change_9789264087873-6-en.

OECD, 2010b. OECD Environmental Outlook to 2050: The Consequences of Inaction.

OECD/IEA, 2012. World energy outlook 2012. Paris: International Energy Agency.

Öko-Institut / Fraunhofer ISI, 2014. Klimaschutzszenario 2050. 1. Modellierungsrunde.

Öko-Institut / Fraunhofer ISI, 2015. Klimaschutzszenario 2050 - 2. Runde.

Öko-Institut / Fraunhofer ISI, 2016. Klimaschutzszenario 2050: Zusammenfassung des 2. Endberichts Studie im Auftrag des Bundesministeriums für Umwelt, Naturschutz, Bau und Reaktorsicherheit.

PBL/ECN, 2011. Naar een schone economie in 2050:routes verkend. Hoe Nederland klimaatneutraal kan worden. PBL Netherlands Environmental Assessment Agency, http://www.pbl.nl/sites/default/files/cms/publicaties/PBL-2011-Routekaart-energie-2050-500083014.pdf.

Peters, G.P., 2016. The 'best available science' to inform 1.5 [deg]C policy choices. Nature Clim. Change 6, 646-649.

Pietzcker, R.C., Ueckerdt, F., Carrara, S., de Boer, H.S., Després, J., Fujimori, S., Johnson, N., Kitous, A., Scholz, Y., Sullivan, P., 2016. System integration of wind and solar power in Integrated Assessment Models: A cross-model evaluation of new approaches. Energy Economics.

Platt's, 2013. World Power Plant Database, Scaling Dynamics of Energy Technologies Model.

Poortinga, W., Steg, L., Vlek, C., Wiersma, G., 2003. Household preferences for energy-saving measures: A conjoint analysis. Journal of Economic Psychology 24, 49-64.

Pye, S., Anandarajah, G., Fais, B., McGlade, C., Strachan, N., 2015. Pathways to deep decarbonization in the United Kingdom.

Rao, A.B., Rubin, E.S., Keith, D.W., Granger Morgan, M., 2006. Evaluation of potential cost reductions from improved amine-based CO2 capture systems. Energy Policy 34, 3765-3772.

Rao, S., Riahi, K., 2006. The role of Non-CO2 greenhouse gases in climate change mitigation: long-term scenarios for the 21st Century. The Energy Journal, 177-200.

Rao, S., Riahi, K., Stehfest, E., Van Vuuren, D., Cho, C., Den Elzen, M., Isaac, M., van Vliet, J., 2008. IMAGE and MESSAGE scenarios limiting GHG concentration to low levels.

Refsgaard, J.C., van der Sluijs, J.P., Brown, J., van der Keur, P., 2006. A framework for dealing with uncertainty due to model structure error. Advances in Water Resources 29, 1586-1597.

Refsgaard, J.C., van der Sluijs, J.P., Højberg, A.L., Vanrolleghem, P.A., 2007. Uncertainty in the environmental modelling process – A framework and guidance. Environmental Modelling & Software 22, 1543-1556.

REN21, 2014. Global Status Report.

Riahi, K., Kriegler, E., Johnson, N., Bertram, C., den Elzen, M., Eom, J., Schaeffer, M., Edmonds, J., Isaac, M., Krey, V., Longden, T., Luderer, G., Méjean, A., McCollum, D.L., Mima, S., Turton, H., van Vuuren, D.P., Wada, K., Bosetti, V., Capros, P., Criqui, P., Hamdi-Cherif, M., Kainuma, M., Edenhofer, O., 2015. Locked into Copenhagen pledges — Implications of short-term emission targets for the cost and feasibility of long-term climate goals. Technological Forecasting and Social Change 90, Part A, 8-23.

Risbey, J., Kandlikar, M., Patwardhan, A., 1996. Assessing integrated assessments. Climatic Change 34, 369-395.

Rogelj, J., Hare, W., Chen, C., Meinshausen, M., 2011. Discrepancies in historical emissions point to a wider 2020 gap between2° C benchmarks and aggregated national mitigation pledges. Environmental Research Letters 6, 024002.

Rogelj, J., Schaeffer, M., Friedlingstein, P., Gillett, N.P., Van Vuuren, D.P., Riahi, K., Allen, M., Knutti, R., 2016b. Differences between carbon budget estimates unravelled. Nature Climate Change 6, 245-252.

Rogelj, J., den Elzen, M., Höhne, N., Fransen, T., Fekete, H., Winkler, H., Schaeffer, R., Sha, F., Riahi, K., Meinshausen, M., 2016a. Paris Agreement climate proposals need a boost to keep warming well below 2 °C. Nature 534, 631-639.

Rogge, K.S., Boedeker, P., Dallinger, D., Fleiter, T., Friedrichsen, N., Klobasa, M., Lehmann, J., Michaelis, J., Pudlik, M., Ragwitz, M., Wietschel, M., 2015. Country report 1: Green niche-innovations in the German electricity system.

Rohde, C., Dütschke, E., Gigli, M., Bles, M., Behavioural Climate Change Mitigation Options - Domain Report Housing, CE Delft (Publication code: 12.7316.01).

Rohracher, H., 2008. Energy systems in transition: contributions from social sciences. International Journal of Environmental Technology and Management 9, 144-161.

Rosenbloom, D., 2017. Pathways: An emerging concept for the theory and governance of low-carbon transitions. Global Environmental Change 43, 37-50.

Rotmans, J., van Asselt, M.B., 2001. Uncertainty management in integrated assessment modeling: towards a pluralistic approach. Environmental monitoring and assessment 69, 101-130.

Roy, R., 2012. Lifestyles, well-being and energy, Global Energy Assessment (2012), pp. 1527–1548.

Sartor, O., Donat, L., Duwe, M., Umpfenbach, K., 2017. Developing 2050 decarbonization strategies in the EU: Insights on good practice from national experiences, Study n°03/2017, IDDRI, Paris, France, 22 p.

Schafer, A., Victor, D.G., 2000. The future mobility of the world population. Transportation Research Part A: Policy and Practice 34, 171-205.

Schäfer, A., Heywood, J.B., Jacoby, H.D., Waitz, I.A., 2009. Transportation in a climate-constrained world. MIT press.

Schmid, E., Knopf, B., 2012. Ambitious mitigation scenarios for Germany: A participatory approach. Energy Policy 51, 662-672.

Schoots, K., Hekkenberg, M., Hammingh, P., 2016. Nationale Energieverkenning 2016.

Schuman, S., Lin, A., 2012. China's Renewable Energy Law and its impact on renewable power in China: Progress, challenges and recommendations for improving implementation. Energy policy 51, 89-109.

Schwanitz, V.J., 2013. Evaluating integrated assessment models of global climate change. Environmental Modelling & Software 50, 120-131.

Shukla, P., Dhar, S., Garg, A., Halsnaes, K., 2007. Balancing energy, development and climate priorities in India: Current trends and future projections. UNEP Risø Centre on Energy, Climate and Sustainable Development, Risø DTU National Laboratory for Sustainable Energy.

Shukla, P.R., Chaturvedi, V., 2012. Low carbon and clean energy scenarios for India: Analysis of targets approach. Energy Economics 34, S487-S495.

Shukla, P.R., Chaturvedi, V., 2013. Sustainable energy transformations in India under climate policy. Sustainable Development 21, 48-59.

Sims, R., Schaeffer, R., Creutzig, F., Cruz-Núñez, X., D'agosto, M., Dimitriu, D., Meza, M.F., Fulton, L., Kobayashi, S., Lah, O., 2014. Transport. Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.

Sims, R.E.H., Schock, R.N., Adegbululgbe, A., Fenhann, J., Konstantinaviciute, I., Moomaw, W., Nimir, H.B., Schlamadinger, B., 2007. Chapter 4: Energy Supply, Internation panel of climate change.

Smil, V., 2000. Perils of long-range energy forecasting: reflections on looking far ahead. Technological Forecasting and Social Change 65, 251-264.

Smil, V., 2008. Long-range energy forecasts are no more than fairy tales. Nature 453, 154-154.

Smith, P., Davis, S.J., Creutzig, F., Fuss, S., Minx, J., Gabrielle, B., Kato, E., Jackson, R.B., Cowie, A., Kriegler, E., van Vuuren, D.P., Rogelj, J., Ciais, P., Milne, J., Canadell, J.G., McCollum, D., Peters, G., Andrew, R., Krey, V., Shrestha, G., Friedlingstein, P., Gasser, T., Grubler, A., Heidug, W.K., Jonas, M., Jones, C.D., Kraxner, F., Littleton, E., Lowe, J., Moreira, J.R., Nakicenovic, N., Obersteiner, M., Patwardhan, A., Rogner, M., Rubin, E., Sharifi, A., Torvanger, A., Yamagata, Y., Edmonds, J., Yongsung, C., 2016. Biophysical and economic limits to negative CO2 emissions. Nature Clim. Change 6, 42-50.

Sørensen, P.B., Elmeskov, J., Frederiksen, P., Jacobsen, J.B., Kristensen, N.B., Morthorst, P.E., Richardson, K., 2015. Converting with care - Status and challenges for Danish climate policy.

Sovacool, B.K., 2016. How long will it take? Conceptualizing the temporal dynamics of energy transitions. Energy Research & Social Science 13, 202-215.

Staub-Kaminski, I., Zimmer, A., Jakob, M., Marschinski, R., 2014. Climate policy in practice: A typology of obstacles and implications for integrated assessment modeling. Climate Change Economics 5, 1440004.

Steckel, J.C., Jakob, M., Marschinski, R., Luderer, G., 2011. From carbonization to decarbonization?—Past trends and future scenarios for China's CO 2 emissions. Energy policy 39, 3443-3455.

Steg, L., Dreijerink, L., Abrahamse, W., 2006. Why are energy policies acceptable and effective? Environment and Behavior 38, 92-111.

Steg, L., 2008. Promoting household energy conservation. Energy policy 36, 4449-4453.

Stehfest, E., Bouwman, L., Van Vuuren, D.P., Den Elzen, M.G., Eickhout, B., Kabat, P., 2009. Climate benefits of changing diet. Climatic change 95, 83-102.

Stehfest, E., van Vuuren, D.P., Kram, T., Bouwman, L., Alkemade, R., Bakkenes, M., Biemans, H., Bouwman, A., den Elzen, M., Janse, J., Lucas, P.L., van Minnen, J., Muller, M., Prins, A.G., 2014. policy applications Integrated Assessment of Global Environmental Change with IMAGE 3.0 - Model description and policy applications.

Stern, N., 2016. Economics: Current climate models are grossly misleading, Nature, pp. 407–409.

Stocker, T.F., 2013. The closing door of climate targets. Science 339, 280-282.

Strachan, N., 2011a. UK energy policy ambition and UK energy modelling—fit for purpose? Energy Policy 39, 1037-1040.

Strachan, N., 2011b. UKERC Energy Research Landscape: Energy Systems Modelling.

Tabi, A., 2013. Does pro-environmental behaviour affect carbon emissions? Energy policy 63, 972-981.

Tavoni, M., Van der Zwaan, B., 2009. Nuclear versus coal plus CCS: a comparison of two competitive base-load climate control options. Environmental Modeling & Assessment 16, 431-440.

Tavoni, M., Socolow, R., 2013. Modeling meets science and technology: an introduction to a special issue on negative emissions. Climatic Change 118, 1-14.

Tavoni, M., Kriegler, E., Riahi, K., van Vuuren, D.P., Aboumahboub, T., Bowen, A., Calvin, K., Campiglio, E., Kober, T., Jewell, J., Luderer, G., Marangoni, G., McCollum, D., van Sluisveld, M., Zimmer, A., van der Zwaan, B., 2015. Post-2020 climate agreements in the major economies assessed in the light of global models. Nature Clim. Change 5, 119-126.

The World Bank, 2015. GDP (current US$) | Data | Table. http://data.worldbank.org/indicator/NY.GDP.MKTP.CD/countries?display=default.

Thema, J., Nanning, S., Buhl, J., Götz, T., Adisorn, T., Kurth, J., Manirjo, N., Echternacht, L., Berg, H., 2014. Country report 4: Green niche-innovations in the German heat system.

Tiefenbeck, V., Staake, T., Roth, K., Sachs, O., 2013. For better or for worse? Empirical evidence of moral licensing in a behavioral energy conservation campaign. Energy Policy 57, 160-171.

Tol, R.S., 1997. On the optimal control of carbon dioxide emissions: an application of FUND. Environmental Modeling and Assessment 2, 151-163.

Tol, R.S.J., 2009. The feasibility of low concentration targets: An application of FUND. Energy Economics 31, Supplement 2, S121-S130.

Townshend, T., Fankhauser, S., Aybar, R., Collins, M., Landesman, T., Nachmany, M., Pavese, C., 2013. The GLOBE climate legislation study: a review of climate change legislation in 33 countries. Rep., GLOBE Int.

Trutnevyte, E., Barton, J., O'Grady, Á., Ogunkunle, D., Pudjianto, D., Robertson, E., 2014. Linking a storyline with multiple models: A cross-scale study of the UK power system transition. Technological Forecasting and Social Change 89, 26-42.

Trutnevyte, E., McDowall, W., Tomei, J., Keppo, I., 2016. Energy scenario choices: Insights from a retrospective review of UK energy futures. Renewable and Sustainable Energy Reviews 55, 326-337.

Turnheim, B., Berkhout, F., 2014. Country report 5: Green niche-innovations in the UK heat system.

Turnheim, B., Håkansson, I., Berkhout, F., 2014. Country report 7: Green niche-innovations in the Dutch mobility system.

Turnheim, B., Berkhout, F., Geels, F., Hof, A., McMeekin, A., Nykvist, B., van Vuuren, D., 2015. Evaluating sustainability transitions pathways: Bridging analytical approaches to address governance challenges. Global Environmental Change 35, 239-253.

UKERC, 2013. The UK energy system in 2050: Comparing Low-Carbon Resilient Scenarios.

UN, 1998. Kyoto protocol to the United Nations Framework Convention on Climate Change, http://unfccc.int/resource/docs/convkp/kpeng.pdf.

UN, 2008. World population prospects.

UN, 2010. Milestones on the road to 2012: The Cancun Agreements. http://unfccc.int/key_steps/cancun_agreements/items/6132.php.

UN, 2015. Paris Agreement.

UNEP, 2016. The Emissions Gap Report 2016 - the UNEP Synthesis Report, Nairobi.

UNFCCC, 2009. Report of the Conference of the Parties on its fifteenth session, held in Copenhagen from 7 to 19 December 2009, http://unfccc.int/resource/docs/2009/cop15/eng/11a01.pdf#page=4.

UNFCCC, 2011. Framework Convention on Climate Change: Compilation of economy-wide emission reduction targets to be implemented by Parties included in Annex I to the Convention.

US EIA, 2014. International Energy Statistics. http://www.eia.gov/cfapps/ipdbproject/iedindex3.cfm?tid=2&pid=28&aid=7&cid=CG6,CG5,&syid=2005&eyid=2011&unit=MK.

van Asselt, M.B.A., Beusen, A.H.W., Hilderink, H.B.M., 1996. Uncertainty in integrated assessment: A social scientific perspective. Environmental Modeling & Assessment 1, 71-90.

van Asselt, M.B.A., Rotmans, J., 2002. Uncertainty in integrated assessment modelling. Climatic Change 54, 75-105.

Van der Sluijs, J.P., 2002. A way out of the credibility crisis of models used in integrated environmental assessment. Futures 34, 133-146.

van der Zwaan, B.C.C., Rösler, H., Kober, T., Aboumahboub, T., Calvin, K.V., Gernaat, D.E.H.J., Marangoni, G., McCollum, D., 2013. A cross-model comparison of global long-term technology diffusion under a 2°C climate change control target. Climate Change Economics 04, 1340013.

van Sluisveld, M.A.E., Gernaat, D.E., Ashina, S., Calvin, K.V., Garg, A., Isaac, M., Lucas, P.L., Mouratiadou, I., Otto, S.A., Rao, S., 2013. A multi-model analysis of post-2020 mitigation efforts of five major economies. Climate Change Economics 4, 1340012.

van Sluisveld, M.A.E., Harmsen, J.H.M., Bauer, N., McCollum, D.L., Riahi, K., Tavoni, M., van Vuuren, D.P., Wilson, C., van der Zwaan, B., 2015. Comparing future patterns of energy system change in 2 °C scenarios with historically observed rates of change. Global Environmental Change 35, 436-449.

van Sluisveld, M.A.E., Martínez, S.H., Daioglou, V., van Vuuren, D.P., 2016a. Exploring the implications of lifestyle change in 2 °C mitigation scenarios using the IMAGE integrated assessment model. Technological Forecasting and Social Change 102, 309-319.

van Sluisveld, M.A.E., Boot, P., Hammingh, P., Notenboom, J., van Vuuren, D.P., 2016b. Low-carbon energy scenarios in north-west European countries - Report of the PBL round-table of June 10th, 2016, PBL Netherlands Environmental Assessment Agency.

van Vliet, J., van den Berg, M., Schaeffer, M., van Vuuren, D.P., den Elzen, M., Hof, A.F., Mendoza Beltran, A., Meinshausen, M., 2012. Copenhagen Accord Pledges imply higher costs for staying below 2°C warming. Climatic Change 113, 551-561.

van Vuuren, D.P., O'Neill, B.C., 2006. The Consistency of IPCC's SRES Scenarios to 1990–2000 Trends and Recent Projections. Climatic Change 75, 9-46.

van Vuuren, D.P., 2007. Energy systems and climate policy - Long-term scenarios for an uncertain future, Copernicus Institute of Sustainable Development. Utrecht University.

van Vuuren, D.P., Lucas, P.L., Hilderink, H., 2007a. Downscaling drivers of global environmental change: Enabling use of global SRES scenarios at the national and grid levels. Global Environmental Change 17, 114-130.

van Vuuren, D.P., den Elzen, M.G.J., Lucas, P.L., Eickhout, B., Strengers, B.J., van Ruijven, B., Wonink, S., van Houdt, R., 2007b. Stabilizing greenhouse gas concentrations at low levels: an assessment of reduction strategies and costs. Climatic Change 81, 119-159.

van Vuuren, D.P., Riahi, K., 2008. Do recent emission trends imply higher emissions forever? Climatic Change 91, 237-248.

van Vuuren, D.P., Hoogwijk, M., Barker, T., Riahi, K., Boeters, S., Chateau, J., Scrieciu, S., van Vliet, J., Masui, T., Blok, K., Blomen, E., Kram, T., 2009. Comparison of top-down and bottom-up estimates of sectoral and regional greenhouse gas emission reduction potentials. Energy Policy 37, 5125-5139.

van Vuuren, D.P., Edmonds, J., Smith, S.J., Calvin, K.V., Karas, J., Kainuma, M., Nakicenovic, N., Riahi, K., van Ruijven, B.J., Swart, R., Thomson, A., 2010. What do near-term observations tell us about long-term developments in greenhouse gas emissions? Climatic Change 103, 635-642.

van Vuuren, D.P., Riahi, K., 2011. The relationship between short-term emissions and long-term concentration targets. Climatic Change 104, 793-801.

van Vuuren, D.P., Stehfest, E., Elzen, M.G., Kram, T., Vliet, J., Deetman, S., Isaac, M., Goldewijk, K.K., Hof, A., Beltran, A.M., 2011. RCP2. 6: exploring the possibility to keep global mean temperature increase below 2 C. Climatic Change 109, 95-116.

van Vuuren, D.P., Kok, M.T., Girod, B., Lucas, P.L., de Vries, B., 2012a. Scenarios in global environmental assessments: key characteristics and lessons for future use. Global Environmental Change 22, 884-895.

Van Vuuren, D.P., Riahi, K., Moss, R., Edmonds, J., Thomson, A., Nakicenovic, N., Kram, T., Berkhout, F., Swart, R., Janetos, A., 2012b. A proposal for a new scenario framework to support research and assessment in different climate research communities. Global Environmental Change 22, 21-35.

van Vuuren, D.P., Stehfest, E., 2013. If climate action becomes urgent: the importance of response times for various climate strategies. Climatic Change 121, 473-486.

van Vuuren, D.P., Kok, M., 2015. Integrated Assessment Modelling, in: Pattberg, P.H., Zelli, F. (Eds.), Theorising global environmental governance: Key findings and future questions. Edward Elgar Publishing, pp. 119-125.

Vaughan, N.E., Gough, C., 2016. Expert assessment concludes negative emissions scenarios may not deliver. Environmental Research Letters 11, 095003.

Victor, D., 2015. Climate change: Embed the social sciences in climate policy. Nature.

Voinov, A., Bousquet, F., 2010. Modelling with stakeholders. Environmental Modelling & Software 25, 1268-1281.

Voinov, A., Seppelt, R., Reis, S., Nabel, J.E.M.S., Shokravi, S., 2014. Values in socio-environmental modelling: Persuasion for action or excuse for inaction. Environmental Modelling & Software 53, 207-212.

Von Borgstede, C., Andersson, M., Johnsson, F., 2013. Public attitudes to climate change and carbon mitigation—Implications for energy-associated behaviours. Energy Policy 57, 182-193.

Walker, W.E., Harremoës, P., Rotmans, J., van der Sluijs, J.P., van Asselt, M.B.A., Janssen, P., Krayer von Krauss, M.P., 2003. Defining Uncertainty: A Conceptual Basis for Uncertainty Management in Model-Based Decision Support. Integrated Assessment 4, 5-17.

Weber, C., Perrels, A., 2000. Modelling lifestyle effects on energy demand and related emissions. Energy Policy 28, 549-566.

Weimer-Jehle, W., 2006. Cross-impact balances: a system-theoretical approach to cross-impact analysis. Technological Forecasting and Social Change 73, 334-361.

Weyant, J., 2009. A perspective on integrated assessment. Climatic Change 95, 317-323.

Weyant, J., Knopf, B., De Cian, E., Keppo, I., van Vuuren, D.P., 2013. Introduction to the EMF28 Study on scenarios for transforming the European energy system. Climate Change Economics 4, 1302001.

Weyant, J., Kriegler, E., 2014. Preface and introduction to EMF 27. Climatic Change 123, 345-352.

Wilson, C., 2012. Input, Output, and Outcome Metrics for Assessing Energy Technology Innovation. In A. Grubler & C. Wilson (Eds.), Energy Technology Innovation: Learning from Historical Successes and Failures. Cambridge: Cambridge University Press. doi:10.1017/CBO9781139150880.009.

Wilson, C., 2012a. Up-scaling, formative phases, and learning in the historical diffusion of energy technologies. Energy Policy 50, 81-94.

Wilson, C., Grubler, A., Bauer, N., Krey, V., Riahi, K., 2012. Future capacity growth of energy technologies: are scenarios consistent with historical evidence? Climatic Change 118, 381-395.

Wilson, C., Grubler, A., 2013. Lessons Learnt from the Energy Technology Innovation System, in: A. Grubler & C. Wilson (Eds.) (Ed.), Energy Technology Innovation: Learning from Historical Successes and Failures, Cambridge: Cambridge University Press. doi:10.1017/CBO9781139150880.032.

Wilson, C., Kriegler, E., van Vuuren, D.P., Guivarch, C., Frame, D., Krey, V., Osborn, T.J., Schwanitz, V.J., Thompson, E.L., 2017. Evaluating Process-Based Integrated Assessment Models of Climate Change Mitigation, http://pure.iiasa.ac.at/14502/1/WP-17-007.pdf.

Wise, M., Calvin, K., Thomson, A., Clarke, L., Bond-Lamberty, B., Sands, R., Smith, S.J., Janetos, A., Edmonds, J., 2009. Implications of limiting CO2 concentrations for land use and energy. Science 324, 1183-1186.

Wood, G., Newborough, M., 2003. Dynamic energy-consumption indicators for domestic appliances: environment, behaviour and design. Energy and buildings 35, 821-841.

World Nuclear Association, 2014. WNA Reactor Database. http://world-nuclear.org/nucleardatabase/rdResults.aspx?id=27569 (accessed 9.21.14).

World Nuclear Association, 2016. Plans For New Reactors Worldwide. World Nuclear Association.

Wright, R.L., 2011. Unilever Sustainable Living Plan — Inspiring Sustainable Living, Expert Insights Into Consumer Behaviour & Unlever's Five Levers for Change.

Yang, L., Mingqi, P., Deetman, S., Hof, A., 2011. Country report on mitigation and adaptation policies in China. Institute of Policy and Management, Chinese Academy of Sciences (CAS-IPM)/PBL Netherlands Environment Assessment Agency, Beijing/Bilthoven.

Zhang, M., Mu, H., Ning, Y., 2009. Accounting for energy-related CO 2 emission in China, 1991–2006. Energy Policy 37, 767-773.

9

Chapter 10

Samenvatting en conclusies

10.1 Inleiding

Tijdens de klimaatconferentie van Parijs in 2015 is er besloten om de opwarming van de aarde te beperken tot "*well below 2°C*" sinds het pre-industriële niveau en indien mogelijk zelfs tot 1.5°C. Beleidsmakers die deze doelstelling nastreven worden geconfronteerd met vele uitdagingen. Dit komt allereerst omdat de vastgestelde doelstelling gedurende een langdurige tijdschaal moet worden gerealiseerd, veel langer dan gebruikelijk bij beleidsbepaling. Naast de langdurige tijdschaal worden beleidsmakers ook geconfronteerd met allerlei onzekerheden, mede door vertraagde en ondoorzichtige terugkoppelingen in zowel het natuurlijke als het menselijke systeem (o.a. door de lange atmosferische levensduur van bepaalde broeikasgassen of door sociale reactietraagheid). Ook is er sprake van een grote verscheidenheid aan opvattingen, meningen en belangen met betrekking tot de verschillende beleidsoplossingen, zoals de rol van technologie of gedragsverandering.

Door de jaren heen zijn er verschillende vormen van onderzoek gebruikt om de toekomst te verkennen en zo de keuzes voor beleidsmakers makkelijker te maken. Deze vormen van onderzoek kunnen grofweg worden ingedeeld in drie groepen: (1) het gebruik van een historische kader als referentie, (2) kennis van deskundigen, en (3) modelmatige scenarioanalyse. Van al deze onderzoeksvormen is modelmatige scenarioanalyse vermoedelijk het meest toegepast. Modelmatige scenarioanalyses worden uitgevoerd middels het gebruik van rekenmodellen die inzichten combineren vanuit de natuurwetenschappen en de technische -en economische wetenschappen binnen één gestructureerd en consistent raamwerk. Het geheel van de beschikbare kennis over menselijke en natuurlijke systeemverandering, vertaald in wiskundige formules, wordt ook wel het "*Integrated Assessment Model*" (IAM) genoemd. Door IAMs te gebruiken kan er inzicht worden verkregen in de te verwachte verandering in het mondiale systeem over een bepaalde periode.

IAM-berekeningen laten zien dat als de huidige trends zich voorzetten, de wereldgemiddelde temperatuur kan stijgen tot ongeveer 3,6°C tot 5,2°C aan het eind van deze eeuw (met een 90% waarschijnlijkheid) (Rogelj et al., 2016a). IAMs kunnen ook worden gebruikt om de consequenties van beleidsverandering of beleidsdoelen te bestuderen. Door IAMs specifiek te koppelen aan de 2°C klimaatdoelstelling kunnen "*tweegradenpaden*" worden gedefinieerd, welke inzichten geven in de nodige systeemveranderingen over de beleidshorizon. Door diverse IAMs over de hele wereld is er een veelheid aan tweegradenpaden uitgewerkt, die samen een visie vormen over hoe de samenleving aan de 2°C klimaatdoelstelling zou kunnen voldoen. IAMs kunnen bijvoorbeeld een beeld schetsen van (1) een kostenoptimale beleidsstrategie, maar ook (2) het effect van het uitsluiten van specifieke technologieën binnen een beleidsstrategie en (3) het effect van het maken van vertraagde beleidskeuzes op het behalen van ambitieuze klimaatdoelen en de daarbij verwachte kosten. Het vijfde *Assessment Report* (AR5), uitgebracht door het *Intergovernmental Panel on Climate Change* (IPCC) van de Verenigde Naties, biedt het volledige overzicht van de beschikbare literatuur over mogelijke beleidsstrategieëen en hun effecten op het mondiale systeem (Clarke et al., 2014).

De door IAMs beschreven tweegradenpaden hebben bijgedragen aan de internationale klimaatonderhandelingen (o.a. gedurende de klimaatconferentie van Parijs in 2015) door mogelijke oplossingsrichtingen te beschrijven (UN, 2015; G7, 2015). Echter, de ontwikkelde tweegradenpaden worden ook door velen bekritiseerd. Deze kritiek op tweegradenpaden richt zich voornamelijk op (i) de veronderstelde grootschalige beschikbaarheid van "negatieve emissies" (oftewel de relatief grotere afvang dan uitstoot van fossiele koolstofdioxide (CO_2) emissies) (Anderson en Peters, 2016;. Fuss et al, 2014), (ii) de gepresenteerde snelle opschaling van diverse technologische en niet-technologische elementen, (iii) de gepresenteerde snelle systeemtransitie (Höök et al, 2012., Smil, 2008) (Iyer et al, 2015.), (iv) het gebrek aan vertaling van mondiale naar lokale inzichten (Grübler, 2004), en (v) het ontbreken van een sociale dimensie in de toegepaste rekenmodellen (Li, 2017, Victor, 2015).

Gezien de complexiteit van de werkelijkheid zijn de inzichten van IAMs noodzakelijkerwijs gebaseerd op vereenvoudigde en geïdealiseerde veronderstellingen. Deze vereenvoudigingen vertalen de complexe werkelijkheid in bredere systeempatronen, die vervolgens in modelvergelijkingen kunnen worden vastgelegd. Dit maakt scenarioanalyse uitvoerbaar en reproduceerbaar. Gelijktijdig betekent dit dus ook dat de diversiteit en complexiteit binnen de echte systeemprocessen grotendeels buiten beschouwing worden gelaten. De resultaten, die de IAM-rekenmodellen produceren, zijn dus vaak niet in overeenstemming met het verwachte verloop van werkelijke systeemverandering in de loop van de tijd (Clarke et al, 2009;. Iyer et al, 2015;. Riahi et al, 2015). Scenarioanalyses worden doorgaans dus meer beschouwd als verkenningen, en niet als voorspellingen.

In het kader van de 2°C klimaatdoelstelling is het van belang om na te gaan hoe IAMs presteren in het formuleren van beleidsstrategieën die de noodzakelijke systeemverandering weergeven om de 2°C klimaatdoelstelling te behalen. In dit proefschrift is dit onderzocht door het resultaat van IAMs in het licht te zetten van andere onderzoeksperspectieven. Daarnaast is het van belang beter te begrijpen hoe IAMs toegepast worden binnen beleidsplanningsprocessen.

De hoofdonderzoeksvraag is daarom als volgt geformuleerd:

Welke aanvullende inzichten kunnen worden verkregen met betrekking tot de kansen en uitdagingen van de 2°C klimaatdoelstelling bij een evaluatie van modelmatige tweegradenpaden in combinatie met andere onderzoeksmethoden?

Om de centrale onderzoeksvraag te beantwoorden, is de hoofdonderzoeksvraag onderverdeeld in de volgende deelonderzoeksvragen:

- ***Deelonderzoeksvraag 1:*** Welke aanvullende inzichten kunnen regionale modelmatige scenarioanalyses bieden?
- ***Deelonderzoeksvraag 2:*** Welke aanvullende inzichten kunnen worden verkregen door tweegradenpaden in het licht te zetten van andere onderzoeksperspectieven buiten het domein van IAMs?
- ***Deelonderzoeksvraag 3:*** Welke aanvullende inzichten kunnen worden verkregen als er tweegradenpaden worden gemaakt op basis van informatie buiten het reguliere domein van IAMs?
- ***Deelonderzoek vraag 4:*** Hoe worden IAM-uitkomsten gebruikt en toegepast in beleidsplanningsprocessen, gericht op een duurzame en koolstofarme samenleving?

Om IAM-resultaten in het licht van andere onderzoeksperspectieven te zetten zijn er verschillende evaluatiemethodieken toegepast. Tabel 10-1 bied hiervan een overzicht.

Table 10-1 - Overzicht van de gebruikte evaluatiemethoden per hoofdstuk

		OV1	OV2		OV3		OV4
ANALYTISCHE LENS	**EVALUATIEMETHODE**	**H. 2**	**H.3**	**H. 4**	**H. 5**	**H.6**	**H.7**
HISTORISCH KADER	1 Kwalitatieve vergelijking		•			•	
	2 Kwantitatieve vergelijking		•			•	
DESKUNDIGEN	3 Kwalitatieve vergelijking			•		•	•
	4 Kwantitatieve vergelijking			•		•	•
IAM	5 Mono-modelleringsraamwerk				•	•	
	6 Uitgebreid modelleringsraamwerk	•	•	•	•	•	•

10.2 Samenvatting en conclusies "2°C door verschillende lenzen"

10.2.1 Deelonderzoeksvraag 1: Welke aanvullende inzichten kunnen regionale scenario-analyses bieden?

In **hoofdstuk 2** zijn de oplossingsstrategieën van meerdere IAMs geanalyseerd in het kader van de 2°C klimaatdoelstelling, waarbij specifiek gelet is op de ontwikkelingen in verschillende wereldeconomieën. Dergelijke multi-modelstudies zijn bedoeld om robuste informatie en/of controverses wat betreft benodigde systeemveranderingen te identificeren, gebruikmakend van de verschillen tussen de IAMs. In de analyse van hoofdstuk 2 is gekeken naar de belangrijke trends van vijf grote wereldeconomieën (China, India, Europa, de Verenigde Staten van Amerika en Japan), zoals de ontwikkeling van de CO_2-uitstoot, de Kaya-identiteit, sectorale emissiereducties en de samenstelling van energietechnologieën in het energiesysteem. Om de uitgebeelde systeemveranderingen in perpsectief te plaatsen zijn de regionale resultaten vergeleken met de mondiale resulaten. De bestudeerde tweegradenpaden zijn gebaseerd op een universele koolstofprijs om een kosteneffectief transitiepad te simuleren. Hoewel dit leidt tot de goedkoopste mondiale mitigatiestrategie, leidt dit niet tot de meest eerlijke verdeling van landeninspanningen.

De multi-modelstudie laat zien dat regionale patronen kunnen variëren binnen en tussen IAMs (zie figuur 10-1 en 10-2). Belangrijke inzichten die hier uit volgen zijn:

- De trends van de meeste regionale tweegradenpaden zijn vergelijkbaar met de trend van het mondiale tweegradenpad: zo laten alle regionale tweegradenpaden een snelle omslag zien van stijgende naar dalende CO_2-uitstoot en vertonen ze allemaal een grootschalige toepassing van negatieve emissies later in de eeuw. Ondanks de overeenkomsten verschillen de snelheden in de uitgebeeldde systeemverandering nog aanzienlijk tussen de regio's. Regio's met momenteel een hoge of een verwachte groei in CO_2-uitstoot (zoals China, India en de Verenigde Staten) laten hogere CO_2-emissiereducties zien dan andere regio's (zie figuur 10-1, paneel a). Daarnaast worden er ook regionale verschillen zichtbaar gemaakt in IAMs met betrekking tot plaatselijke omstandigheden en potentiëlen. Zo laten alle IAMs, bijvoorbeeld, een relatief lage beschikking van hernieuwbaar potentieel in Japan zien (zie figuur 10-1, paneel b).

- Grote verschillen worden weergegeven in de uitgebeeldde tweegradenpaden tussen de IAMs (Figuur 10-2, paneel b-d). Enkele verschillen zijn te herleiden naar de voorkeuren van IAMs voor een specifieke oplossingsstrategie. Sommige modellen hebben een relatief grotere voorkeur voor het gebruik van bio-elektriciteit

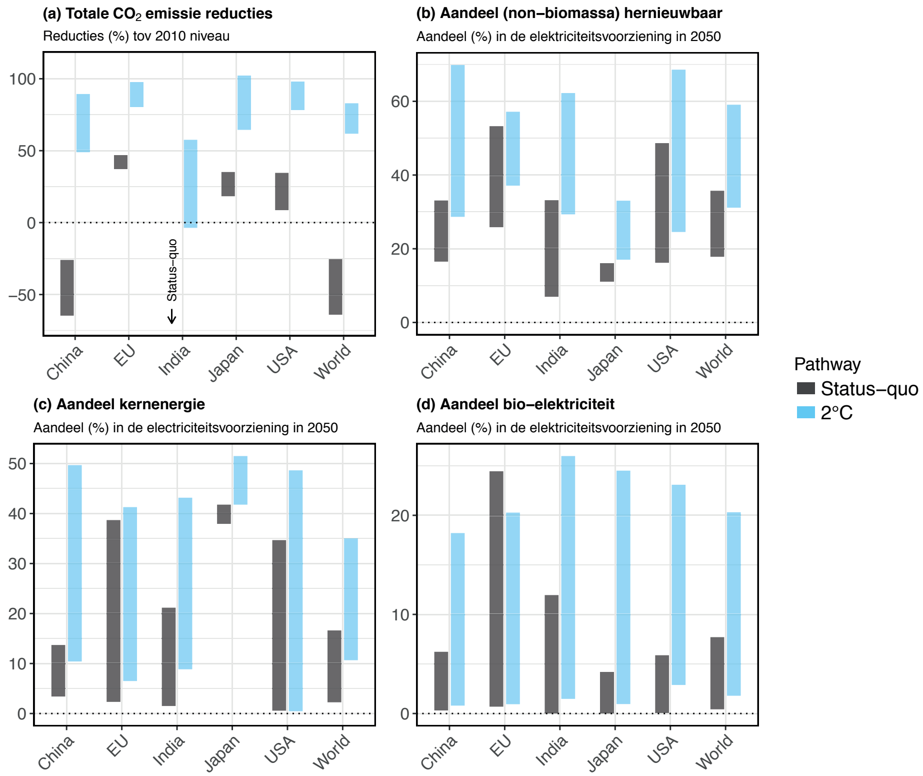


Figure 10-1 (a-d) - Overzicht van weergegeven regionale en mondiale systeemveranderingen van IAMs (IMAGE, MESSAGE, REMIND, TIAM-ECN, WITCH) in het jaar 2050 (de balken geven de range aan modeluitkomsten weer). De paden "status-quo" en "2°C" worden respectievelijk als RefPol of RefPol-450 aangeduid in hoofdstuk 2. Onder status-quo veronderstellingen is de verwachting dat de CO_2-uitstoot van India aanzienlijk zal toenemen (240-410%) (niet weergegeven).

(waaronder het IMAGE model en in mindere mate ook het TIAM-ECN model, zoals blijkt uit paneel d), wat samenhangt met een voorkeur voor een oplossingsstrategie gebaseerd op CO_2-afvang en negatieve emissies. Andere modellen vertonen een voorkeur voor de inzet van (niet-biomassa gerelateerde) hernieuwbare energievoorziening (zoals het MESSAGE en het REMIND model). Het WITCH model weerspiegelt een diversere aanpak die gebaseerd is op technologie-substitutie en energie-efficiëntie verbeteringen.

10.2.2 Deelonderzoeksvraag 2: Welke aanvullende inzichten kunnen worden verkregen door tweegradenpaden in het licht te zetten van andere onderzoeksperspectieven buiten het domein van IAMs?

In hoofdstuk 2 is gekeken naar de systeemontwikkeling en veranderingssnelheden behorende bij tweegradenpaden vanuit het IAM-onderzoeksperspectief. Door deze

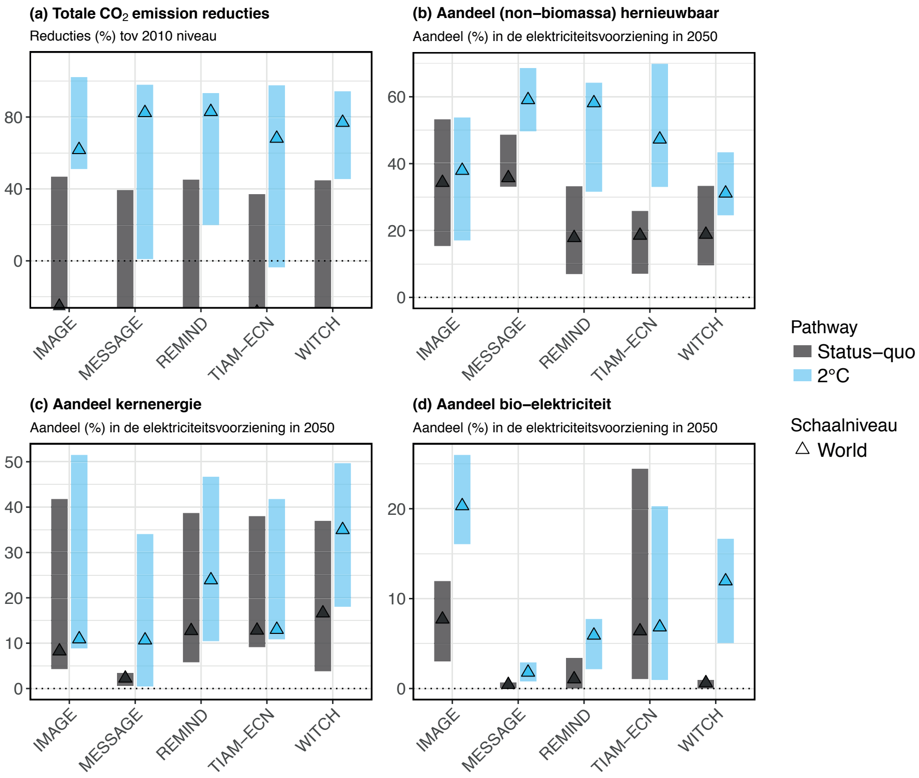


Figure 10-2 (a-d) - Overzicht van weergegeven regionale en mondiale systeemveranderingen van IAMs in het jaar 2050 (de range geeft de regionale range weer, gebaseerd op resultaten voor China, India, de VS, de EU en Japan). In het wereldgemiddelde zijn alle regio's meegenomen. De paden "status-quo" en "2°C" worden respectievelijk als RefPol of RefPol-450 aangeduid in hoofdstuk 2.

IAM-resultaten te belichten met andere onderzoeksperspectieven buiten het IAM-domein kunnen er aanvullende inzichten worden verkregen met betrekking tot mogelijke systeemontwikkeling en veranderingssnelheden in de loop van de tijd. In hoofdstuk 3 zijn daardoor de mondiale IAM-resultaten systematische vergeleken met gemeten veranderingssnelheden uit het verleden. Tevens zijn de mondiale IAM-resultaten vergeleken met de verwachtingen van deskundigen betreffende de toekomstige systeemverandering (hoofdstuk 4).

In **hoofdstuk 3** is er gebruik gemaakt van een brede reeks aan indicatoren die mogelijke systeemveranderingen op twee verschillende niveaus kunnen meten (op systeem- en energietechnologieniveau). De gebruikte systeem-gerelateerde indicatoren omvatten (1) de gemiddelde jaarlijkse emissiereductie, als een weerspiegeling van de totale systeemdruk bij tweegradenpaden, en (2) de gemiddelde jaarlijkse investeringen in de energievoorziening, als een weerspiegeling van de nodige maatschappelijke inspanning voor het bewerkstelligen van een energietransitie. De gebruikte technologie-gerelateerde indicatoren omvatten (3) de gemiddelde jaarlijkse groei in het geïnstalleerd vermogen voor energietechnologieën, als een graad voor de technologische veranderingssnelheid, en (4) de totale doorlooptijd en maximale omvang van technologische marktopname. Om de historische en gemodelleerde uitkomsten met elkaar te kunnen vergelijken zijn deze genormaliseerd op basis van de relatieve systeemgroei in het geheel gedurende een bepaalde periode (waarbij systeemgroei is gedefinieerd als de groei van het totaal bruto binnenlands product, de totale investeringen in het elektriciteitssysteem, de totale elektriciteitsproductie of het totaal geïnstalleerd vermogen van technologiën in de energievoorziening). Voor elke technologie-gerelateerde indicator is de systeemverandering vergeleken met de groei van de snelst groeiende energietechnologie in het verleden (steenkool). Een zelfde vergelijking is uitgevoerd voor elke systeem-gerelateerde indicator, waarbij de mondiale waarde is vergeleken met de best presterende wereldregio, zoals gevonden in de literatuur.

Uit dit onderzoek is gebleken dat de berekende absolute veranderingssnelheden in tweegradenpaden voor technologie-gerelateerde indicatoren grotendeels binnen gerapporteerde historische waarden blijft voor de komende tien jaar. Halverwege de 21ste eeuw zal de absolute groeisnelheid echter toenemen tot een niveau dat historisch gezien nog niet is voorgekomen. Als men naar de genormaliseerde indicatoren kijkt, waarbij de algemene groei van het systeem mee in beschouwing is genomen, dan blijkt dat de veranderingspatronen van de tweegradenpaden de historische waarden niet overschrijden. Hoewel technologische verandering (of systeemverandering) dus op een veel grotere schaal moet worden uitgerold dan ooit in het verleden is bewerkstelligd, blijkt dat de relatieve veranderingssnelheid wel vergelijkbaar is met transities uit het verleden. De keuze voor een normalisatiemethode heeft echter wel invloed op deze beoordeling.

In **hoofdstuk 4** worden de IAM-resultaten vergeleken met de verwachtingen van deskundigen op het gebied van energietechnologieën en technologische groei. De verwachtingen van deze technologiedeskundigen zijn verzameld middels een digitaal enquêteprotocol dat erop gericht is vergelijkbare en consistente resultaten te werven bij een uiteenlopende groep van energietechnologiedeskundigen. In dit onderzoek is speciaal gekeken naar de technologische ontwikkeling van windenergie, zonne-energie, kernenergie, bio-elektriciteit (zowel met als zonder CO_2-afvangsinstallaties) en fossiel-gestookte elektriciteitsproductie (zowel met als zonder CO_2-afvangsinstallaties). De deskundigen zijn geselecteerd op basis van hun bijdragen aan toonaangevende onderzoeksrapporten, zoals het 4^{e} *Assessment Report* van het IPCC (Sims et al., 2007), de *Global Energy Assessment* (GEA, 2012), het *Special Report on Renewable Energy Sources and Climate Change Mitigation* (Edenhofer et al., 2011) en het *Global Status Report* (REN21 2014). In totaal zijn 39 experts bereid gevonden om deel te nemen aan de enquête, die gezamenlijk zowel academici, overheidsinstanties, de particuliere sector als intergouvernementele organisaties vertegenwoordigen. De groep deelnemers beschikt daardoor zowel over theoretische als praktische kennis over toekomstige technologische verandering.

Alle 39 deskundigen hebben een vergelijkbare enquête ingevuld, waarbij gebruik is gemaakt van eenzelfde soort vraagstelling. De eerste vraag betrof de relatieve rol van verschillende energietechnologieën in de energievoorziening. Gevraagd is deze technologieën te rangschikken op volgorde van hun bijdragen aan de energievoorziening in 2050. Deze vraag is voorgelegd aan alle deelnemende deskundigen, waarbij geen onderscheid is gemaakt tussen expertisegebieden. Vervolgens werden de deskundigen gevraagd om een kwantitatieve schatting te maken van de omvang van het geïnstalleerde vermogen en het verwachte aandeel hiervan in de totale elektriciteitsproductie voor hun eigen expertisegebied. De deskunden zijn gevraagd deze schattingen te maken voor zowel de korte termijn (2030) als middellange termijn (2050), voor zowel een baseline (status-quo) als een tweegradenpad. Na het invullen van de eigen inschattingen zijn de deskundigen geconfronteerd met de gemiddelde inschatting van zeven IAMs. De deskundigen konden de gemiddelde IAM- inschattingen

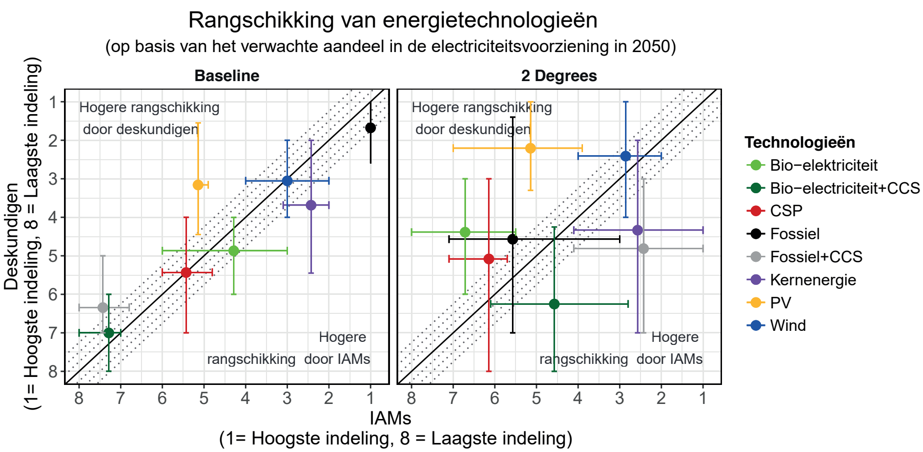


Figure 10-3 – De gemiddelde rangschikking op volgorde van aandeel aan de energievoorziening in 2050. Rangschikking bepaald door 39 deskundigen en 7 IAMs. Het weergegeven bereik van antwoorden vertegenwoordigd het 15[e] en 85[e] percentiel van de totale resultaten. De diagonale lijn en het gearceerde gebied verbeelden waar deskundigen en IAMs in overeenstemming zijn over de rangschikking. PV staat voor electriciteit opgewekt uit fotovoltaische zonnecellen. CSP staat voor geconcentreerde zonnestroom. CCS staat voor CO_2-opslaginstallatie.

vervolgens evalueren door deze als "zeer laag", "laag", "aannemelijk", "hoog" of "zeer hoog" te beoordelen, wederom voor de korte termijn (2030) en middellange termijn (2050) en voor baseline en tweegraden-veronderstellingen.

Uit dit onderzoek is gebleken dat de IAMs en de deskundigen ongeveer gelijke ontwikkelingen verwachten in de mondiale energievoorziening onder status-quo veronderstellingen voor 2050 (zie figuur 10-3, *Baseline* paneel), op het aandeel van zonne-energie in de totale elektriciteitsproductie na. In tweegradenpaden bestaat er meer onderling verschil (zie figuur 10-3, *2 Degrees* paneel), wat af te leiden is uit het grotere bereik van antwoorden voor zowel de deskundigen als IAMs. In vergelijking met de deskundigen zijn IAMs relatief optimistisch ten aanzien van energieproductie gekoppeld aan CO_2-afvangsinstallaties en kernenergie. Omgekeerd kennen de experts een grotere rol toe aan zonne-energie en bio-elektriciteit (zonder CO_2-afvang) in de mondiale energievoorziening onder tweegraden veronderstellingen voor 2050. Duidelijke verschillen zijn er gevonden tussen IAMs en deskundigen in de ingeschatte grootheden voor geïnstalleerd vermogen in 2050, met name voor bio-elektriciteit, zonne-energie en CO_2-afvangsinstallaties. Hoewel deskundigen een belangrijke rol voorzien voor CO_2-afvang onder tweegraden veronderstellingen, verwachten ze dat met name de bijdrage wordt geleverd via fossiel-gestookte elektriciteitsproductie, gekoppeld aan CO_2-afvangsinstallaties. Hierdoor wordt de ingeschatte bijdrage van bio-elektriciteit gekoppeld aan CO_2-afvangsinstallaties, zoals grootschalig wordt toegepast in IAMs, als optimistisch beschouwd door de experts. Het verschil in de verwachte rol en de ingeschatte omvang van bio-elektriciteit in de electriciteitssector duidt op een meer structureler verschil in aannames tussen IAMs en deskundigen.

Beide hoofdstukken hebben inzicht gegeven in de gemodelleerde systeemreacties van IAMs ten opzichte van andere onderzoeksperspectieven. Hoewel de vergelijking van IAMs met dergelijke onderzoeksperspectieven sterk afhankelijk is van de gebruikte indicatoren, kunnen op basis van deze analysen sommige systeemveranderingen als meer robuust en andere als meer controversieel worden beschouwd. Zo is vastgesteld dat de korte termijn technologische systeemverandering, zoals ingeschat door IAMs, binnen historische waarden blijft in absolute en relatieve omvang. Op de middellange termijn blijft dit gelden voor relatieve groei. De geschiedenis biedt echter maar een beperkt kader om de mogelijkheden van toekomstige systemverandering te toetsen, gezien de veranderende omstandigheden (het verleden kent bijvoorbeeld geen gecoördineerde aanpak waarin de wereld een tweegraden klimaatdoelstelling nastreeft) en het gebrek aan een voorwaartse blik (geen informatie over innovatiekracht). Deskundigen kunnen daarentegen anticiperen en een inschatting maken over de te verwachte (korte termijn) ontwikkelingen. Ze houden daarbij over het algemeen rekening met een bredere set aan overwegingen dan rekenmodellen, zoals de maatschappelijke en politieke overwegingen die gelden voor bio-elektriciteit, kernenergie en CO_2-afvang.

10.2.3 Deelonderzoeksvraag 3: Welke aanvullende inzichten kunnen worden verkregen als er tweegradenpaden worden gemaakt op basis van informatie buiten het reguliere domein van IAMs?

Naast het toetsen van rekenmodelweergaven van mondiale systeemverandering binnen de bestaande kennisstructuur, kan ook inzicht worden verkregen in toekomstige systeemverandering door te kijken naar andere specialisatiegebieden, die over het algemeen niet worden meegenomen binnen de IAMs. IAMs kijken, bijvoorbeeld, traditioneel nauwelijks naar gedragsverandering in het behalen van de 2°C klimaatdoelstelling. In **hoofdstuk 5** wordt daarom een relatief eenvoudige methode gepresenteerd waarin meer diepgang wordt gezocht in de rol die gedragsveranderingen kunnen spelen in het behalen van de 2°C klimaatdoelstelling. Voor dit onderzoek is gebruik gemaakt van het *Integrated Model to Assess the Global Environment* (IMAGE) om de impact van gedragsverandering te beoordelen. Het IMAGE-model is bijzonder geschikt voor dit type onderzoek, gezien de relatief hoge resolutie op een sectoraal -en serviceniveau. Vanwege dit detailniveau is het mogelijk om een reeks van gedragsveranderingen in te voeren in het IMAGE-model op het niveau van huishoudens, mobiliteit, energievoorziening en afvalbeheer. De aannames over duurzamer gedrag zijn gebaseerd op voorbeelden die op dit moment beschikbaar zijn in de hedendaagse (westerse) samenleving. Ook wordt in dit onderzoek aangenomen dat de voorgestelde gedragsveranderingen op de korte termijn en wereldwijd kunnen plaatsvinden, zodat het effect daarvan bestudeerd kan worden over de korte tot middellange termijn.

Uit het onderzoek is gebleken dat de voorgestelde gedragsveranderingsmaatregelen een flinke reductie in CO_2-uitstoot kunnen bewerkstelligen: 13% in de residentiële sector en 35% in mobiliteit, ten opzichte van de baseline situatie in 2050. In een tweegradenpad kunnen de gedragsveranderingen aanvullend zijn op de meer technologie-georiënteerde systeemveranderingen die normaliter in de rekenmodellen worden aangenomen. Ondanks overlap leiden de gedragsveranderingen tot een lagere energievraag (door bijvoorbeeld meer gebruik te maken van openbaar vervoer in plaats van privé vervoer) en daarmee tot lagere mitigatiekosten. Het onderzoek laat daarmee zien dat gedragsverandering een belangrijke rol kan hebben in het behalen van de 2°C klimaatdoelstelling, ondanks de beperkte aandacht in de huidige model-literatuur.

Om verdere inzichten te verkrijgen in hoe het handelen van maatschappelijke actoren effect kan hebben op het behalen van de 2°C klimaatdoelstelling, kijkt **hoofdstuk 6** verder naar de rol van deze factoren op modelberekeningen. Hoewel IAM-berekeningen elementen van overheidshandelen en het gedrag van maatschappelijke actoren meenemen op basis van verhaallijnen, zijn deze vaak gebaseerd op relatief theoretische overwegingen of vertaald naar vrij abstracte veronderstellingen rond, bijvoorbeeld, vertraging in beleid (Kriegler et al., 2014a; Nakicenovic et al, 2000; O'Neill et al, 2014). In dit onderzoek wordt gebruik gemaakt van een serie van socio-technische casestudies om de gedragsveronderstellingen bij maatschappelijke actoren te onderbouwen. Deze casestudies hebben de huidige situatie ten aanzien van (duurzame) niche-innovatie in kaart gebracht met betrekking tot (1) de sturende actoren in de energietransitie en (2) hun huidig handelen en effecten op systeemverandering.

Het onderzoek is uitgevoerd in samenwerking met onderzoekers uit de transitiewetenschappen die zich bezig houden met het onderzoeken van de socio-technische ontwikkelingen in de loop van de tijd. Er is daarbij gebruik gemaakt van het *Multi-Level Perspective* (MLP) principe. Er zijn belangrijke verschillen tussen de MLP methode en de principes van *Integrated Assessment Modelling*. Deze fundamentele verschillen zijn o.a. te vinden in het verschil in (1) hoe veranderingen uitgelegd worden (verhaallijnen tegenover doorrekeningen), (2) de analytische focus (het beschrijven van de rol van actoren en bijbehorende complexiteit versus versimpeling van transities tot voornamelijk economische en technologische overwegingen) en (3) de gebruikte middelen en indicatoren om de verandering te duiden (kwalitatieve tegenover kwantitatieve indicatoren). Om tot een interactie te komen tussen beide onderzoeksmethoden is er gebruik gemaakt van gezamenlijk gebruikte concepten, samengenomen in de transitieverhaallijn. De transitieverhaallijn weerspiegelt een waargenomen gedragspatroon binnen verscheidene MLP-diepteanalyse die door IAMs kan worden toepast in de doorrekeningen. Binnen deze transitieverhalen is vooral gekeken naar de duiding van systeemverandering waarbij men kan spreken over *niche momentum* en *systeemtraagheid*. Deze begrippen zijn zowel binnen de MLP als IAMs belangrijk, waardoor dit het mogelijk maakt om de MLP-diepteanalysen te relateren aan de IAM-doorrekeningen.

Voor het onderzoek zijn meerdere MLP-diepteanalysen gebruikt, dat wil zeggen een tal van nationale casestudies binnen Europa gericht op een breed scala aan niche-ontwikkelingen in de elektriciteitssector, de gebouwde omgeving en de transportsector. Uit deze casestudies is een indicatie van niche momentum afgeleid op basis van drie analytische dimensies, waaronder (1) innovatietrajecten en marktontwikkelingen (technisch-economisch), (2) actoren en sociale netwerken (sociaal-cognitief), en (3) overheidshandelen en gevoerd beleid van de afgelopen 10-15 jaar. De indicatie van niche momentum geeft inzicht in mogelijke korte termijn systeemverandering waar

IAMs rekening mee kunnen houden (bijvoorbeeld door extra voorkeur of afkeur in te voeren voor een bepaalde ontwikkeling). De MLP-analysen bieden ook inzichten in de actoren die betrokken zijn bij het doorontwikkelen van niche-innovaties, waar twee deelgroepen kunnen worden herkend: (1) de gevestigde orde, die bestaande praktijken wil behouden door deze te vervangen met een (technologisch) alternatief en (2) nieuwe actoren, die nieuwe praktijken omarmen (o.a. gedrag) en daarmee een regimeverschuiving tot stand brengen. Door zowel de indicatie van niche momentum als de deelgroepen mee in beschouwing te nemen kunnen er twee nieuwe transitiepaden worden ontworpen, beide gericht op het behalen van de (Europese) klimaatdoelstelling.

Uit de IAM-doorrekeningen is gebleken dat beide transitiepaden de mogelijkheid bieden om aan het Europees klimaatbeleid tot 2050 te voldoen. Heel specifiek speelde tussen de twee transitiepaden de vraag of het mogelijk is om aan het Europese klimaatdoel in 2050 te voldoen zonder “negatieve emissie” technologieën toe te passen (oftewel bio-elektriciteit met CO_2-afvangsinstallaties) en kernenergie. In aanwezigheid van dergelijke energietechnologieën is het mogelijk de transitie geleidelijker te laten verlopen op de korte termijn omdat de elektriciteitssector extra emissies (op korte termijn en vanuit andere sectoren) kan compenseren. Wanneer “negatieve emissies” niet mogelijk zijn is dus een snellere transitie nodig in alle sectoren. Onder de “nieuwe actoren”-veronderstelling betekent dit dus meer gebruik van hernieuwbare energiebronnen en doelbewuste energievraagvermindering (gedragsverandering). Ondanks een relatief laag niche momentum volgens de MLP-diepteanalysen, benadrukt het onderzoek wederom dat gedragsverandering een belangrijke speler kan zijn in het behalen van lange termijn klimaatdoelen. Belangrijk is te beseffen dat de meer onderbouwde aannames en specificaties van gedragsverandering en de ingeschatte bijdrage van een regimeverschuiving slechts beperkt kunnen worden weergegeven in rekenmodellen. Het onderzoek leidt daarom ook tot aanbevelingen over hoe een verdere uitwerking van de methodiek kan leiden tot meer geïnformeerde en verschillende transitiepaden.

10.2.4 Deelonderzoeksvraag 4: Hoe worden IAM-uitkomsten gebruikt en toegepast in beleidsplanningsprocessen gericht op een duurzame en koolstofarme samenleving?

Het laatste hoofdstuk behandelt de rol en bijdrage van modelberekeningen in de nationale beleidsvorming voor de middellange termijn (2050). In het verleden hebben de doorrekeningen van IAMs geleid tot de onderbouwing van beleidsdoelstellingen binnen de Europese Unie (EU). De EU heeft bijvoorbeeld gekozen voor een emissiereductiedoelstelling van 80% tot 95% voor 2050 ten opzichte van het 1990 niveau, wat een directe vertaling is van de modelgebaseerde doorrekeningen van tweegradenpaden in het 4e *Assessment Report* van de IPCC (European Commission, 2009;. Gupta et al, 2007). Deze doelstelling wordt op Europees -en lidstaatniveau vertaald naar concreet beleid. Hoewel er inmiddels aanzienlijke inspanningen zijn verricht om de voortgang van de Europese lidstaten te monitoren, bestaat er nog geen centraal systeem dat toezicht houdt op de geformuleerde middellange termijn ambities en doelstellingen op het niveau van lidstaten. Hoewel de Europese Energie Unie alle lidstaten heeft opgeroepen om inzicht te geven in hun beleidsplannen voor de middellange termijn, is dit proces nog niet voltooid. Het is daarom belangrijk te onderzoeken hoe verschillende Europese lidstaten omgaan met de doelstellingen, hun middellange termijn beleidsstrategie bepalen en of IAMs daarin een beleidsondersteunende rol spelen.

In **hoofdstuk 7** wordt het beleidsproces en de rol van modeldoorrekeningen rond lange termijn beleidsdoelstellingen van een select aantal Europese lidstaten nader bestudeerd (ook wel ex-ante beleidsevaluatie genoemd). Om de voortgang te evalueren is er zowel kwalitatief als kwantitatief naar de verschillen tussen lidstaten gekeken. Kwalitatief is er gekeken naar (1) het beleidsplanningsproces voor de middellange termijn, (2) de rolverdeling en waarborging van modelkennis, en (3) hoe stakeholders in het proces worden meegenomen. Daarnaast is er ook een kwantitatieve vergelijking gemaakt van de modeldoorrekeningen van enkele beschikbare nationale langetermijn verkenningsstudies. Deze nationale modeldoorrekeningen zijn ook uiteengezet tegen de modeldoorrekeningen gedaan met verschillende Europese rekenmodellen met een resolutie op lidstaatniveau.

Uit het onderzoek is gebleken dat de nationale beleidsprocessen in de vijf EU-lidstaten zeer divers zijn, in termen van 1) hoe lange termijn planning institutioneel is vastgelegd, 2) de waarborging en rolverdeling van het rekenmeesterschap en 3) de deelneming van (publieke) stakeholders. Modelstudies worden gebruikt als een ex-ante beleidsevaluatieinstrument in alle onderzochte lidstaten. De diepgang en organisatie in de nationale beleidsplanningprocessen verschilt echter duidelijk. Zo heeft het Verenigd Koningkrijk een geïnstitutionaliseerd jaarlijkse ex-ante beleidsevaluatiecyclus, die voornamelijk uitgevoerd wordt door een onafhankelijke klimaatraad, conform aan de nationale klimaat wet -en regelgeving. Het klimaatbeleid van Frankrijk wordt veel meer gekenmerkt door een betrokkenheid van een groot aantal (publieke en private) stakeholdergroepen en een veelheid van modelstudies. De interactie tussen de stakeholdergroepen en het georganiseerde rekenmeesterschap (binnen een koepelorganisatie) in Frankrijk heeft tot een hogere legitimiteit geleid van ex-ante beleidsevaluatiestudies in de beleidsvorming. Een voorkeurstransitiepad is vermoedelijk op basis van dit werk opgenomen in het huidige klimaatbeleid. Denemarken heeft een bindend klimaatdoel en heeft gekozen voor een bepaald voorkeurspad naar een koolstofvrije economie in lijn met de EU 2050 doelstelling. De ex-ante beleidsevaluatiestudies zijn daardoor nadere uitwerkingen van verschillende variaties op het voorkeurspad. De Duitse regering besteedt ex-ante beleidsevaluatiestudies van beleidsinspanningen over de middellange termijn uit aan onafhankelijke nationale onderzoeksgroepen. Hoewel de klimaatdoelstelling niet in de wet is vastgelegd in Duitsland, dragen modelstudies frequent bij aan de strategische planning van klimaatbeleid. In Nederland is ex-ante beleidsevaluatie van de beleidsinspanningen over de middellange termijn geconcentreerd rond een beperkt aantal studies van aangewezen overheidsinstellingen. Doordat er geen duidelijke doelstellingen voor 2050 zijn, is ook het transitiepad voor Nederland tot 2050 nog tamelijk onduidelijk ten opzichte van enkele andere landen.

Uit de kwantitatieve vergelijking van recent gepubliceerde nationale langetermijn verkenningsstudies blijkt dat er grote verschillen zijn in de informatiedichtheid, focus en hun toepassing in beleid. Over het algemeen worden zowel verkennende als beschrijvende scenario's doorgerekend in de nationale modelstudies, waarmee verschillende beleidsbeslissingen nader worden toegelicht of vergeleken. Een interessante bevinding is dat bijna alle nationale modelstudies een directe vertaling van de collectieve Europese doelstelling voor 2050 hanteren binnen de nationale context. In vergelijking met de Europese rekenmodellen, die de Europese doelstelling "verdelen" over de lidstaten op basis van relatieve kosten en reductiemogelijkheden, kan worden geconcludeerd dat nationale doorrekenstudies daarmee een beperkt beeld tonen. Nog opvallender is dat alle nationale modelstudies bijzonder weinig aandacht besteden aan de ontwikkelingen in, of interactie met, omliggende landen binnen de EU of verder. Dit geld voor zowel voor weergaven in de ontwikkeling van de energiemarkt en de bredere (collectieve) klimaatmitigatie-inspanningen.

10.3 Een perspectief op toekomstige uitdagingen en kansen voor 2°C

Tot nu toe zijn enkel nog de afzonderlijke resultaten en inzichten van de hoofdstukken betreffende het mogelijke verloop van toekomstige systeemverandering besproken. We komen nu terug op de hoofdonderzoeksvraag: wat kunnen we leren over de kansen en uitdagingen bij tweegradenpaden als we alle verkregen inzichten combineren? Door gebruik te maken van verschillende onderzoeksperspectieven (o.a. rekenmodellen, historische vergelijkingen, inschattingen van deskundigen en MLP-diepteanalysen) kan een beter onderbouwd antwoord worden gegeven op welke kansen en uitdagingen er in het verschiet liggen bij een transitie naar een koolstofvrije samenleving in lijn met de 2°C klimaatdoelstelling. Tabel 10-2 geeft hiervan een voorbeeld.

Table 10-2 – Synthese van de resultaten verkregen uit de verschillende onderzoeksperspectieven naar tweegradenpaden (alle resultaten zijn gericht op het voldoen aan de 2°C klimaatdoelstelling).

	(A)		(B)		(C)
Referentie	**Hoofdstuk 3**		**Hoofdstuk 4**		**Hoofdstuk 6**
Schaalniveau	**Mondiaal**		**Mondiaal**		**Europa**
Bekeken indicator	**Gemiddeld geïnstalleerd vermogen per jaar [*1] (genormalizeerd met BBP en gestandaardiseerd t.o.v. de best presterende technologie uit de geschiedenis (=100))**		**Rangschikking op basis van het aandeel in de elektriciteitsvoorziening in 2050 [*3] (1 = hoogste indeling) (8 = laagste indeling)**		**Niche momentum [*4]**
Analytisch onderzoeksperspectief	**IAM (2030-2050)**	**HISTORISCH[*2]**	**IAM (2050)**	**DESKUNDIGEN (2050)**	**MLP[*5] (2015-2016)**
Zonne-energie	42	18	5.1	2.2	Laag/hoog
Windenergie	41	37	2.9	1.7	Medium/hoog
Kernenergie	12	25	2.6	4.3	-
Bio-elektriciteit excl. CO_2-afvang	0	7	6.7	4.6	Laag/medium
Bio-elektriciteit incl. CO_2-afvang	5	0	4.6	6.3	-
Fossiele excl. CO_2-afvang	1 (steenkool)	100 (steenkool)	5.6	4.6	-
Fossiel incl. CO_2-afvang	3 (aardgas)	0	2.4	4.8	-

* 1: Het genormalizeerde gemiddeld geïnstalleerd vermogen verwijst naar de groei in vermogen per jaar (GW / jr), gedeeld door de totale omvang van de economie (totale BBP, in de periode 1980-1012) om te corrigeren voor de algehele groei in het energiesysteem tussen beide onderzochte tijdsperioden. Vervolgens zijn de waarden gestandardiseerd naar de snelst groeiende energietechnologie vanuit het verleden (steenkool). De relatieve afstand t.o.v. deze historische benchmark wordt beschouwd als een maat voor mogelijk beschikbaar groeipotentiaal.

* 2: De periode waarin de gemiddelde vermogensgroei is bepaald verschilt per technologie: voor zonne-energie (2003-2013), windenergie (2003-2013), kernenergie (1980-1990), bio-elektriciteit (2005-2011) en fossiel brandstofgebruik (2003-2012).

* 3: De waarde vertegenwoordigt de gemiddelde waarde van de rankschikking opgegeven door 39 deskundigen over 8 energietechnologieën onder een 2°C klimaatdoelstelling veronderstelling in 2050 (waaronder energievoorziening uit fossiele brandstoffen, fossiele brandstoffen incl. CO_2-afvang, windenergie, zonnestroom (zowel fotovoltaische cellen als geconcentreerde zonnestroom), kernenergie, bio-elektriciteit en bio-elektriciteit incl. CO_2-afvang). Voor IAMs is de rangschikking bepaald door het gemiddelde aandeel van een technologie in de energievoorziening per technologie te rangschikken naar grootte (gebaseerd op 7 IAMs).

* 4: De indicator "niche momentum" is een kwalitatieve beoordeling van het doorbraakpotentieel van technologische en niet-technologische niche-innovaties onttrokken uit een MLP analyse op drie niveaus: (1) innovatietrajecten en marktontwikkelingen (technisch-economisch), (2) netwerk en maatschappelijk actoren (sociaal-cognitief), en (3) het overheidshandelen en beleid van de afgelopen 10-15 jaar.

* 5: MLP: Multi-Level Perspective (Socio-technische transitiewetenschappen)

- **Overeenstemming tussen onderzoeksperspectieven:** Alle onderzoeksperspectieven die in dit proefschrift gebruikt zijn onderschrijven een substantiële bijdrage voor windenergie in het behalen van de 2°C klimaatdoelstelling. Hoewel de groeisnelheid van windenergie bijzonder snel is in het tweegradenpad, is de uitbouw van nieuwe capaciteit niet sneller dan andere succesvolle energietechnologieën in het verleden (kolom A). Dit suggereert dat de groeisnelheid mogelijk haalbaar is gegeven de juiste omstandigheden. Ook de deskundigen benadrukken de cruciale rol van windenergie in de energievoorziening in 2050 (kolom B), waarbij de deskundigen zelfs een hogere bijdrage van wind verwachten dan de rekenmodellen. Bovendien is ook het huidige niche momentum voor verandering hoog (kolom C).

- **Beperkte overeenstemming tussen onderzoeksperspectieven:** De verschillende onderzoeksperspectieven geven een wat meer gevarieerd beeld rond het ontwikkelingspad van zonne-energie. Hoewel twee van de onderzoeksperspectieven (IAMs en deskundigen) zonne-energie een belangrijke rol toebedelen in 2050, verschillen de uitkomsten per indicator onderling. Met name de deskundigen kennen een belangrijke rol aan PV toe, terwijl de rekenmodellen wat meer afwachtend zijn. Volgens de MLP-diepteanalysen is het huidige niche momentum voor zonne-energie laag al dan hoog gegeven de context (kolom C).

- **Verschillen tussen de onderzoeksperspectieven:** Voor een breed scala aan energietechnologieën leveren de onderzoeksperspectieven verschillende visies op. Zo wordt kernenergie door de rekenmodellen geïdentificeerd als een belangrijke energietechnologie voor de toekomstige energievoorziening (kolom B). Desondanks hebben de deskundigen een andere toekomstverwachting verwoord voor de rol van kernenergie in een koolstofvrije samenleving (kolom B). Ook voor bio-elektriciteit bestaat er geen eenduidig beeld, hoewel het verschil in de context moet worden geplaatst van het wel of niet koppelen aan CO_2-afvangsinstallaties. In IAMs wordt bio-elektriciteit in combinatie met CO_2-afvang als de belangrijkste oplossingmethode gezien om de 2°C klimaatdoelstelling binnen bereik te houden. Bio-elektriciteit heeft daardoor zonder CO_2-opvang enkel een beperkte toepassing binnen IAM-modelstudies. Het omgekeerde beeld wordt weergegeven door de deskundigen die het onwaarschijnlijk achten dat de combinatie van bio-elektriciteit met CO_2-afvang grootschalig beschikbaar kan worden gemaakt in 2050 en daardoor enkel enig potentieel zien voor bio-elektriciteit op de middellange termijn. Het verleden kan hier weinig handvatten bieden omdat deze technologie niet eerder is toegepast. Soortgelijke overwegingen zijn te vermelden bij fossiel-gestookte elektriciteitscentrales met CO_2-afvang. Hoewel zowel IAMs als deskundigen een rol zien voor fossiele brandstoffen binnen de 2°C klimaatdoelstelling veronderstellingen in 2050, zijn de rekenmodellen stelliger in hun weergave van fossiele energievoorziening in combinatie met CO_2-afvang dan de deskundigen (kolom B).

Men kan er vanuitgaan dat de kansen voor toekomstige systeemverandering in lijn met de 2°C klimaatdoelstelling groter zijn voor die technologieën waarmee de onderzoeksperspectieven in overeenstemming zijn. Op de punten waar de onderzoeksperspectieven niet in overeenstemming zijn, impliceert dit dat er een aanzienlijke uitdaging is wat betreft de technische mogelijkheden, kosten of maatschappelijke steun. De resultaten van deze synthese moeten echter in context worden geplaatst, gezien (1) de beperkte focus op enkel de electriciteitssector, (2) de beperkte beschikbaarheid van indicatoren voor een één-op-één vergelijking van onderzoeksperspectieven, (3) het beperkt aantal onderzochte doorrekenstudies, deskundigen en MLP-diepteanalysen, die ten grondslag liggen aan het resultaat, (4) het gebruik van gemiddelde waarden en (5) de invloed van tijd op het gegeven resultaat (bijv. de invloed van de kernramp in Fukushima in 2011, het gesloten Parijs Akkoord in 2015). De resultaten van deze synthese kunnen daarom enkel als illustratief worden beschouwd.

Tenslotte, hoewel het onderzoek geen antwoord kan geven over de algemene haalbaarheid van de 2°C klimaatdoelstelling, kan een systematisch vergelijking van meerdere analytische onderzoeksperspectien dienen als een platform om verschillende vakgebieden nader tot elkaar te brengen. Door toekomstige systeemverandering in het licht te zetten van meerdere (inter)disciplinaire perspectieven kan er kritischer worden gekeken naar de drijfveren en barrières achter een transitie naar een koolstofvrije samenleving in lijn met de 2°C klimaatdoelstelling. Als zodanig kan een systematisch georganiseerde evaluatiecyclus van onderzoeksperspectieven bijdragen aan een betere *framing* en *identificatie* van mogelijke systeemveranderingen.

10.4 Aanbevelingen voor vervolgonderzoek

Het evalueren van lange termijn energiesysteemverandering in het licht van de 2°C klimaatdoelstelling is een veel omvattende klus, waarin vele disciplinaire inzichten, methoden en instrumenten geraadpleegd kunnen worden. Uit het huidige onderzoek kunnen drie richtingen voor vervolgonderzoek worden aangestipt:

- **Blikverruiming bij evaluatietoepassingen:** In het huidige onderzoek zijn er maar een beperkt aantal technologie-specifieke en systeembrede indicatoren in het licht van andere analytische perspectieven gezet. Hoewel de energietransitie een speerpunt is in het kader van het voldoen aan de 2°C klimaatdoelstelling, is het van belang om een breder perspectief in acht te nemen. Deze blikverruiming kan gevonden worden door verder aanvullende focusgebieden en indicatoren voor systeemverandering in een evaluatieroutine mee te nemen.

- **Blikverruiming in rekenmodellen:** De rekenmodellen, die in dit onderzoek zijn gebruikt, verbeelden met name systeemverandering vanuit (1) principes van kosteneffectiviteit en (2) technologische substitutiemechanismen onder een 2°C beleidsdruk. Dit kader kan beperkingen opleggen, of blikvernauwing, in de ruimte waarin transitiepaden kunnen worden gezocht en bestudeerd. Vanuit dit onderzoek wordt dus opgeroepen om een breder spectrum van inzichten mee te nemen binnen het toepassingsgebied van modelanalyse en tweegradenpaden. Nieuwe inzichten kunnen er worden verkregen via een nadere samenwerking met andere vakgebieden, zoals de sociale wetenschappen, die een essentiële bijdragen kunnen leveren aan de ontwikkeling van kennis over de uitvoering, ethiek en governance van een koolstofvrije samenleving.

- **Verbreding van het tweegraden dialoog:** Hoofdstuk 6 en 7 belichtte dat er meerdere transitiepaden mogelijk zijn naar een koolstofvrije samenleving in lijn met de 2°C klimaatdoelstelling dan verbeeld in rekenmodellen. Door een bredere (publieke) dialoog aan te gaan gedurende de uitvoering van een lange termijn beleidsevaluatiestudie kunnen er nieuwe inzichten worden verkregen bij een mogelijke transitie naar een koolstof vrije samenleving. Naast het verbeteren van de kennis over complexe systeemveranderingen, kunnen dialogen en participatieve processen met (publieke) maatschappelijke actoren ook voor een groter draagvlak en sociale acceptatie leiden voor specifieke transitierichtingen (Kowarsch, 2016; Voinov en Bousquet, 2010). Om tot betere oplossingsgerichte wetenschap te komen, roept het huidig onderzoek daarom op om maatschappelijke actoren te betrekken binnen het proces van lange termijn beleidsevaluatie.

Acknowledgements

The work that lies before you is the end product of many years of collaboration. Many people have contributed directly and indirectly to the shaping of this thesis for which I would like to express my gratitude. First and foremost, I want to thank my promotor Detlef van Vuuren for allowing me into his team at the start of this all and trusting me with all the responsibilities of a researcher in the science-policy interface. You have learned me about the true meaning of (and available potential in) “up-scaling” by gradually asking for more scenarios, models, sectors and spatial levels to consider, more scientific disciplines to involve, more papers and newsletters to write, more data and databases to be analysed, more visualisation types to consider, more workshops to be hosted, etcetera, during our research throughout the years. Although it looks insurmountable now in retrospect, I have always appreciated the next challenge. I would also like to thank my copromotor, Andries Hof, for the encouragements and for having been ever available to provide feedback and advice.

Secondly, it has been a great honour to have worked with devoted and intrinsically motivated teams, first at Utrecht University and later on at the PBL Netherlands Environmental Assessment Agency. I have been indebted to an earlier formation of the team for both teaching me the ropes in modelling and assessing long-term projections (Jasper, Angelica, Maarten, Paul, Sebastiaan) as well as providing the right environment where we could collectively learn and laugh about all the reoccurring pitfalls and challenges (Sander, David G, Mathijs, Sara, Morna). In a later formation of the team I have also leaned frequently on skills and knowledge of team members that have specialised in more specific topics (Oreane, Harmen Sytze, Vassilis, Barbara, Jonathan, Mark, Annemiek), which allowed me to move more swiftly through my research for which I will be eternally grateful. Next to content, automation, scripting, visualisation and efficiency have definitely been key words describing my time at UU and PBL, with specific mention to Patrick, David B. and Heleen. Wielding Exabyte’s of dynamic data has become less daunting with you guys nearby!

I also would like to thank my co-authors for allowing me to tap into their wealth of knowledge and experience in the field. Despite being first author to the chapters presented in this thesis, it would be delusional to think that I have done this all on my own strength. In particular, I thank Charlie Wilson for having been very generous in time throughout the years and for continuously providing valuable feedback which shaped a large part of the presented research.

A

This work has not been carried out in seclusion either, as I have had the pleasure of broadening my horizons in various environments, being linked to specific project consortia and having been housed at various locations. Much I have learned from my international colleagues whom I had the pleasure to meet during project meetings and conferences – thank you all at the LIMITS, AMPERE and PATHWAYS projects for enriching my time as a researcher and helping me develop more critical thinking. More close to home, I have enjoyed meeting and learning from colleagues of various departments at UU and PBL.

I would also like to acknowledge the teams and members behind PBL Young and YES-DC as a hidden driving factor behind this thesis. It has been a pleasure to have been part of a network that mobilises young professionals to engage in extracurricular activities – both from the organising side as well as participating side. Having been at COP21 has been a memorable achievement in my professional life, which would not have been possible without the help of all the involved fellow-professionals. Special shout-out to Menno and Steven, I have enjoyed your enthusiasm and cheekiness during our PBL Young days. It saddens me to think about how our ways have parted now, but I am honoured that you guys have accepted to join in as "paranymphs" during my defence.

Lastly, my friends, housemates and family, thank you for your support and necessary distractions. I would like to specifically acknowledge Cindy, Nóra, Jolanda, Mujgan, Jennifer, Nevena, Magda, Lars, WJ and Vera who have been supportive over the years and willing victims to listen while I talk about computational models. Jennifer, Anke and dad, thank you for proofreading parts of this thesis. Mom, there are no words that describe how much I have appreciated your support, except for the following: *we* hebben het weer gedaan!

Curriculum Vitae

Maria Anna Elisabeth (Mariësse) van Sluisveld was born on May 14th, 1988, in Zoetermeer, the Netherlands. After graduating from secondary school (VWO) in 2006 she studied *Environmental Sciences* at Utrecht University, gradually specialising in the sustainable development of energy and resource use. Immediately after obtaining her university degrees she pursued a career as a research professional. She started out as a researcher in global change modelling for the European Union funded LIMITS-project at the 'Copernicus Institute of Sustainable Development' of Utrecht University in 2012. During this project she got acquainted with integrated assessment modelling and the data analysis of a wide range of model-based scenarios. After completing this project she continued working as a researcher on the European Union funded PATHWAYS project at the 'Climate, Air and Energy' department of the PBL Netherlands Environmental Assessment Agency in 2014. During this project she got acquainted with other fields of study on transition pathways which offered the opportunity 'to see through different [analytical] lenses'. The work carried out during the LIMITS and PATHWAYS projects has been combined into a PhD thesis at Utrecht University in 2017.

List of publications

Peer-reviewed publications

van Sluisveld, M.A.E., Harmsen, J.H.M., Bauer, N., McCollum, D., Riahi, K., Tavoni, M., van Vuuren, D.P., Wilson, C., van der Zwaan, B. (2015) "Comparing future patterns of energy system change in 2°C scenarios with historically observed rates of change", 35, 436-449, Global Environmental Change, doi:10.1016/j.gloenvcha.2015.09.019

van Sluisveld, M.A.E., Herreras Martínez, S.D., Daioglou, V., van Vuuren, D.P., (2015) "Exploring the implications of lifestyle changes in 2°C mitigation scenarios using the IMAGE integrated assessment model", Technological Forecasting and Social Change, doi:10.1016/j.techfore.2015.08.013

Tavoni, M., Kriegler, E., Riahi, K., van Vuuren, D., Aboumahboub, T., Bowen, A., Calvin, K., Campiglio, E, Kober, T., Jewell, J., Luderer, G., Marangoni, G., McCollum, D., **van Sluisveld, M.,** Zimmer, A., van der Zwaan, B (2014) "Post-2020 climate agreements in the major economies assessed in the light of global models", Nature Climate Change, doi:10.1038/nclimate2475

Otto, A.A.C., Gernaat, D.E.H.J., Isaac, M., Lucas, P., **van Sluisveld, M.A.E.,** van den Berg, M., van Vliet, J., van Vuuren, D.P. (2014) "Impact of bio-energy demand on carbon leakage via land use in fragmented regimes with China and EU as first movers", Technological Forecasting & Social Change, 10.1016/j.techfore.2014.01.015

van Sluisveld, M.A.E., Gernaat, D.E.H.J., Lucas, PL, Ashina, S., Calvin, K.V., Garg, A., Isaac, M, Mouratiadou, I., Otto, A.A.C., Rao, S., Shukla, P.R., van Vliet, J., van Vuuren, D.P. (2014) "A multi-model analysis of post-2020 mitigation efforts of five major economies", Climate Change Economics, 04, 1340012, http://dx.doi.org/10.1142/S2010007813400125

van Sluisveld, M.A.E., Worrell, E. (2013) The paradox of packaging optimization – a characterization of packaging source reduction in the Netherlands, Resources, Conservation and Recycling, Volume 73, April 2013, Pages 133-142, ISSN 0921-3449, 10.1016/j.resconrec.2013.01.016.

Worrell, E., **van Sluisveld, M.A.E.** (2013) Material efficiency in Dutch packaging policy Phil. Trans. R. Soc. A March 13, 2013 371 1986 20110570; doi:10.1098/rsta.2011.0570 1471-2962

Submitted for review

van Sluisveld, M.A.E., Harmsen, J.H.M., van Vuuren, D.P., Bosetti, V., Wilson, C., van der Zwaan, B.C.C. "Comparing future patterns of energy system change in 2°C scenarios to expert projections" (in review) (Chapter 4)

A

van Sluisveld, M.A.E., Hof, A.F., van Vuuren, D.P., Carrara, S., Geels, F. Turnheim, B. "Aligning Integrated Assessment Modelling with Socio-Technical Transition insights: an application to low-carbon energy scenario analysis in Europe" (submitted) (Chapter 6)

van Sluisveld, M.A.E., Hof, A.F., van Vuuren, D.P., Criqui, P., Matthes, F.C., Notenboom, J., Pedersen, S.L., Pfluger, B., Watson, J., Boot, P. "Low-carbon strategies towards 2050: a meta-analysis on five national climate and energy planning processes in Europe" (in review) (Chapter7)

Other publications

van Sluisveld, M., Pieter Boot, Pieter Hammingh, Jos Notenboom, Detlef van Vuuren (2016) "Low-carbon energy scenarios in six north-west European countries", PBL Netherlands Environmental Assessment Agency, PBL Publication number: 2507

van Vuuren, D.P., **van Sluisveld, M.,** Hof, A.F. (2015) "Implications of long-term scenarios for medium-term targets (2050)", PBL Netherlands Environmental Assessment Agency, PBL publication number: 1871

van Vuuren, D.P.; Elzen; M. den, Hof; A., Roelfsema; M., Lucas; P.L., **van Sluisveld; M.A.E.,** Gernaat; D.E.H.J., Otto; A.A.C., van den Berg; M., Harmsen; J.H.M., Schaeffer; M., Admiraal, A., "Long-term climate policy targets and implications for 2030" (2014), PBL Netherlands Environmental Assessment Agency, PBL Publication number: 498