2.SM Mitigation pathways compatible with 1.5°C in the context of sustainable development – Supplementary Material

Authors: Piers Forster (UK), Daniel Huppmann (Austria), Elmar Kriegler (Germany), Luis Mundaca (Chile/Sweden), Chris Smith (UK), Joeri Rogelj (Belgium/Austria), Roland Séférian (France)

Table of Content

2.SM.1 Part 1 4

2.SM.1.1 Geophysical relationships and constraints 4

2.SM.1.1.1 Reduced complexity climate models 4

2.SM.1.1.2 Methods for assessing remaining carbon budgets 7

2.SM.1.1.2.1 Median remaining carbon budget basis 7

2.SM.1.1.2.2 Checks on approach 10

2.SM.1.1.2.3 Uncertainties 10

2.SM.1.2 Integrated Assessment Models 12

2.SM.1.2.1 Short introduction to the scope, use and limitations of integrated assessment modelling 12

2.SM.1.2.2 Economics and Policy Assumptions in IAMs 13

2.SM.1.2.3 Technology assumptions and transformation modelling 14

2.SM.1.2.4 Land use and bioenergy modelling in IAMs 15

2.SM.1.2.5 Contributing modelling framework reference cards 16

2.SM.1.2.6 Overview mitigation measures in contributed IAM scenarios 17

2.SM.1.3 Overview of SR1.5 scenario database collected for the assessment in the Chapter 21

2.SM.1.3.1 Configuration of SR1.5 scenario database 21

2.SM.1.3.1.1 Criteria for submission to the scenario database 21

2.SM.1.3.1.2 Historical consistency analysis of submitted scenarios 22

2.SM.1.3.1.3 Verification of completeness and harmonization for climate impact assessment 22

2.SM.1.3.1.4 Validity assessment of historical emissions for aggregate Kyoto greenhouse gases 22

2.SM.1.3.1.5 Plausibility assessment of near-term development 22

2.SM.1.3.1.6 Missing carbon price information 23

2.SM.1.3.2 Contributions to the SR1.5 database by modelling framework 23

2.SM.1.3.3 Overview and scope of studies available in SR1.5 database 25

2.SM.1.3.4 Data collected 26

2.SM.1.4 Scenario classification 27

2.SM.1.5 Mitigation and SDG pathway synthesis 29

References 32

2.SM.2 Part 2 38

2.SM.2.1 Reference card – AIM-CGE 38

2.SM.2.2 Reference card – BET 41

2.SM.2.3 Reference card – C-ROADS 44

2.SM.2.4 Reference card – DNE21 46

2.SM.2.5 Reference card – FARM 3.2 50

2.SM.2.6 Reference card – GCAM 4.2 53

2.SM.2.7 Reference card – GEM-E3 57

2.SM.2.8 Reference card – GENeSYS-MOD 1.0 61

2.SM.2.9 Reference card – GRAPE-15 1.0 .... **64**
2.SM.2.10 Reference card – ETP Model **68**
2.SM.2.11 Reference card – IEA World Energy Model **71**
2.SM.2.12 Reference card – IMACLIM **74**
2.SM.2.13 Reference card – IMAGE **77**
2.SM.2.14 Reference card – MERGE-ETL 6.0 .... **81**
2.SM.2.15 Reference card – MESSAGE(ix)-GLOBIOM **84**
2.SM.2.16 Reference card – POLES **88**
2.SM.2.17 Reference card – REMIND - MAgPIE **91**
2.SM.2.18 Reference card – Shell - World Energy Model **95**
2.SM.2.19 Reference card – WITCH **98**

2.SM.1 Part 1

2.SM.1.1 Geophysical relationships and constraints

2.SM.1.1.1 Reduced complexity climate models

The ‘Model for the Assessment of Greenhouse Gas Induced Climate Change’ (MAGICC6, Meinshausen et al., 2011a), is a reduced complexity carbon-cycle, atmospheric composition and climate model that has been widely used in prior IPCC Assessments and policy literature. This model is used with its parameter set as identical to that employed in AR5 for backwards compatibility. This model has been shown to match temperature trends very well compared to CMIP5 models (Collins et al., 2013; Clarke et al., 2014).

The ‘Finite Amplitude Impulse Response’ (FAIRv1.3, Smith et al., 2018) model is similar to MAGICC but has even simpler representations of the carbon cycle and some atmospheric chemistry. Its parameter sets are based on AR5 physics with updated methane radiative forcing (Etminan et al., 2016). The FAIR model is a reasonable fit to CMIP5 model for lower emission pathways but underestimates the temperature response compared to CMIP5 models for RCP8.5 (Smith et al., 2018). It has been argued that its near-term temperature trends are more realistic than MAGICC (Leach et al., 2018).

The MAGICC model is used in this report to classify the different pathways in terms of temperature thresholds and its results are averaged with the FAIR model to support the evaluation of the non-CO_2 forcing contribution to the remaining carbon budget. The FAIR model is less established in the literature but can be seen as being more up to date in regards to its radiative forcing treatment. It is used in this report to help assess the uncertainty in the pathway classification approach and also used to support the carbon budget evaluation (Section 2.2 and 2.SM.1.1.2).

The section analyses geophysical differences between FAIR and MAGICC to help provide confidence in the assessed climate response findings of the main report (Sections 2.2 and 2.3).

There are structural choices in how the models relate emissions to concentrations and effective radiative forcing. There are also differences in their ranges of climate sensitivity, their choice of carbon-cycle parameters, and how they are constrained, even though both models are consistent with AR5 ranges. Overall their temperature trends are similar for the range of emission trajectories (Figure 2.1 of the main report). However, differences exist in their near-term trends, with MAGICC exhibiting stronger warming trends than FAIR (see Figure 2.SM.1). Leach et al. (2018) also note that that MAGICC warms more strongly than current warming rates. By adjusting FAIR parameters to match those in MAGICC, more than half the difference in mean near-term warming trends can be traced to parameter choices. The remaining differences are due to choices regarding model structure (Figure 2.SM.1).

A structural difference exists in the way the models transfer from the historical period to the future. The setup of MAGICC used for AR5 uses a parametrisation that is constrained by observations of hemispheric temperatures and ocean heat uptake, as well as assessed ranges of radiative forcing consistent with AR4 (Meinshausen et al., 2009). From 1765 to 2005 the setup used for AR5 bases forcing on observed concentrations and uses emissions from 2006. It also ramps down the magnitude of volcanic forcing from 1995 to 2000 to give zero forcing in future scenarios, and solar forcing is fixed at 2009 values in the future. In contrast, FAIR produces a constrained set of parameters from emissions runs over the historic period (1765-2017) using both natural and anthropogenic forcings, and then uses this set to run the emissions model with only anthropogenic emissions for the full period of analysis (1765-2110). Structural choices in how aerosol, CH_4 and N_2O are implemented in the model are apparent (see Figure 2.SM.2). As well as a weaker CH_4 radiative forcing, MAGICC also has a stronger total aerosol effective radiative forcing that is close to the AR4 best estimate of -1.2 Wm^{-2} for the total aerosol radiative forcing (Forster et al., 2007). As a result its forcing is larger than either FAIR or the AR5 best estimate (Figure 2.SM.2), although its median aerosol forcing is well within the IPCC range (Myhre et al., 2013). The difference in N_2O forcings between the models result both from a slightly downwards-revised radiative forcing estimate for N_2O in (Etminan et al., 2016) and the treatment of how the models account for natural emissions and atmospheric lifetime of N_2O. The stronger aerosol forcing and its stronger recovery in MAGICC has the largest effect on near-term trends, with CH_4 and N_2O also contributing to stronger warming trends in the MAGICC model.

TCRE differences between the models are an informative illustration of their parametric differences. (Figure 2.SM.3). In their setups used in this report, FAIR has a TCRE median of 0.38°C (5–95% range of 0.25 to 0.57°C) per 1000 GtO_2 and MAGICC a TCRE median of 0.47°C (5–95% range of 0.13 to 1.02°C) per 1000 $GtCO_2$. When directly used for the estimation of carbon budgets, this would make the remaining carbon budgets considerably larger in FAIR compared to MAGICC. As a result, rather than to use their budgets directly, this report bases its budget estimate on the AR5 TCRE *likely* (greater than 16–84%) range of 0.2 to 0.7°C per 1000 $GtCO_2$ (Collins et al., 2013) (see Section 2.SM.1.1.2).

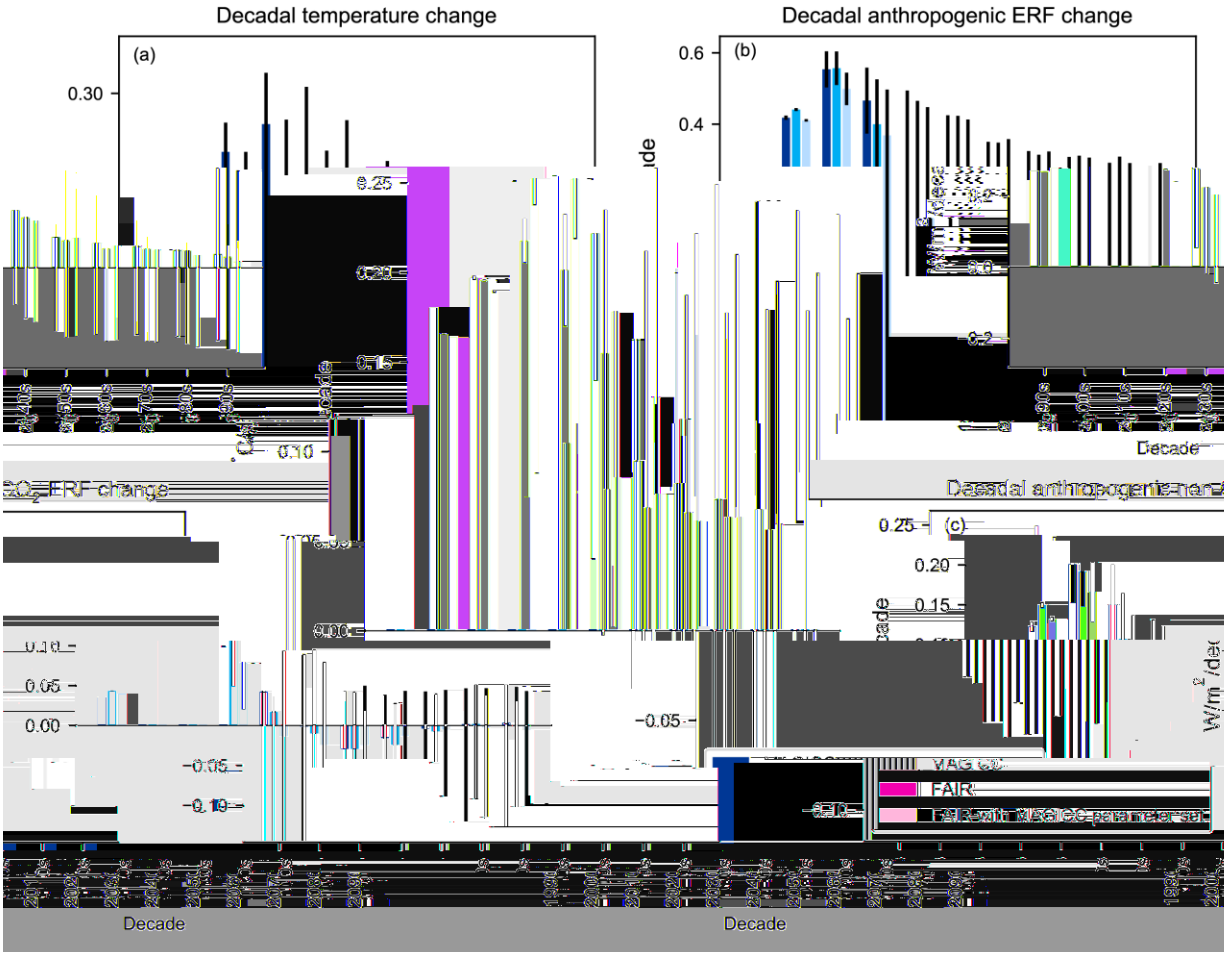


Figure 2.SM.1: Warming rates per decade for MAGICC (dark blue), FAIR (sky blue) and FAIR matching the MAGICC parameter set (light blue) for the scenario dataset used in this report. Bars represent the mean of regression slopes taken over each decade (years 0 to 9) for scenario median temperature changes, over all scenarios. The black bars show the standard deviation over the set of scenarios.

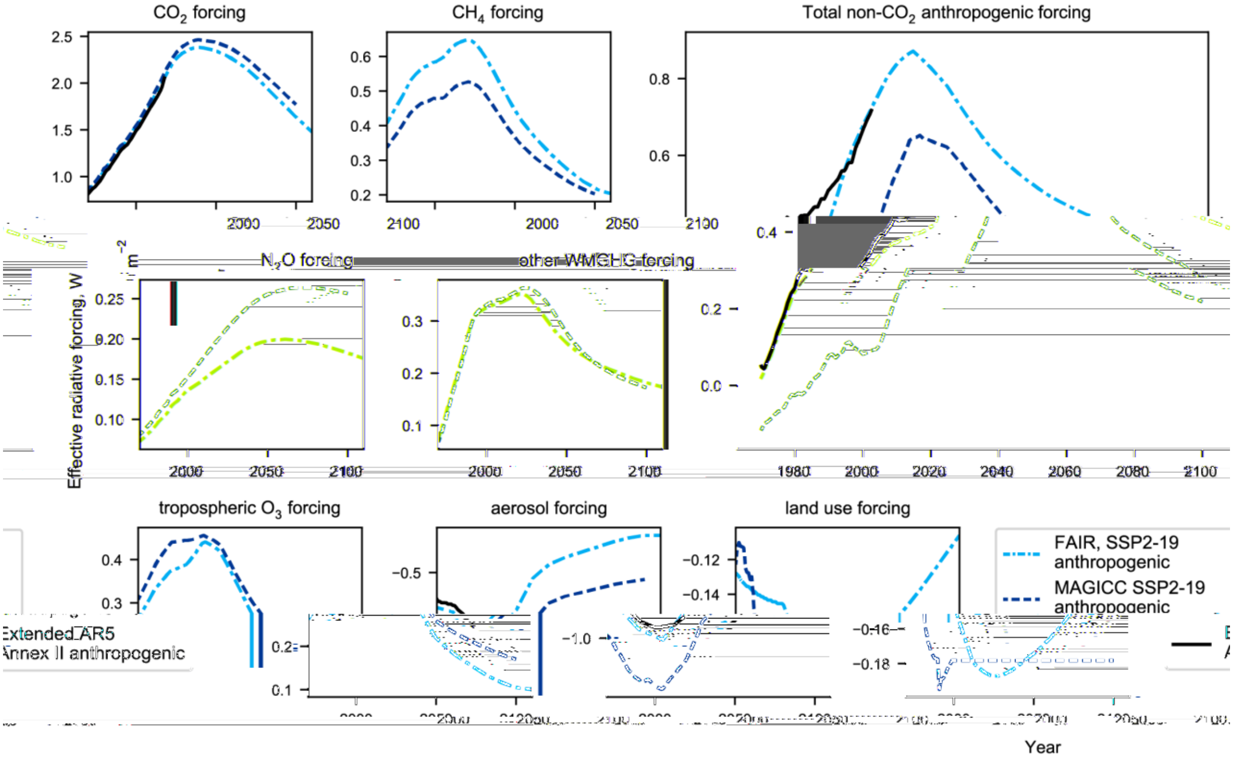


Figure 2.SM.2: Time series of MAGICC (dark blue dashed) and FAIR (sky blue dash-dotted) effective radiative forcing for an example emission scenario for the main forcing agents where the models exhibit differences. AR5 data is from Myhre et al. (2013), extended from 2011 until the end of 2017 with greenhouse gas data from NOAA/ESRL (www.esrl.noaa.gov/gmd/ccgg/trends/), updated radiative forcing approximations for greenhouse gases (Etminan et al., 2016) and extended aerosol forcing following (Myhre et al., 2017).

The summary assessment is that both models exhibit plausible temperature responses to emissions. It is too premature to say that either model may be biased. As MAGICC is more established in the literature than FAIR and has been tested against CMIP5 models, the classification of scenarios used in this report is based on MAGICC temperature projections. There is *medium confidence* in this classification and the likelihoods used at the boundaries could prove to underestimate the probability of staying below given temperatures thresholds if near-term temperatures in the applied setup of MAGICC turn out to be warming too strongly. However, neither model accounts for possible permafrost melting in their setup used for this report (although MAGICC does have a setting that would allow them to be included (Schneider von Deimling et al., 2012, 2015)), so biases in MAGICC could cancel in terms of their effect on long-term temperature targets. The veracity of these reduced complexity climate models is a substantial knowledge gap in the overall assessment of pathways and their temperature thresholds.

The differences between FAIR and MAGICC have a substantial effect on their remaining carbon budgets (see Figure 2.SM.3), and the strong near-term warming in the specific MAGICC setup applied here (Leach et al., 2018) may bias its results to smaller remaining budgets (green line on Figure 2.SM.3). Likewise, the relatively small TCRE in FAIR (compared to AR5) might bias its results to higher remaining budgets (orange line on Figure 2.SM.3). Rather than using the entire model response, only the contribution of non-CO$_2$ warming from each model is used, using the method discussed next.

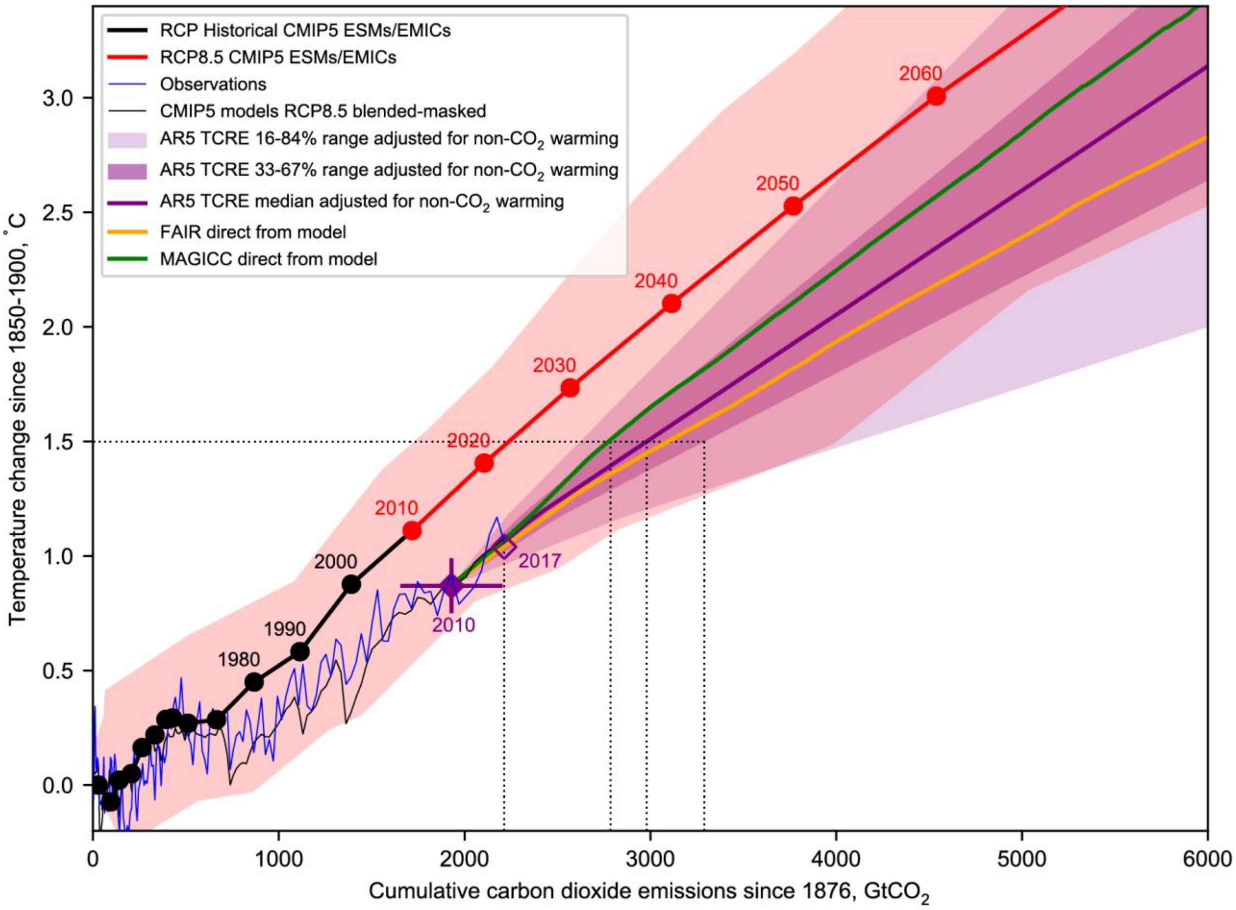


Figure 2.SM.3: This figure follows Figure 2.3 of the main report with two extra lines on each showing FAIR (orange) and MAGICC (green) results separately. These additional lines show the full model response averaged across all scenarios and geophysical parameters.

2.SM.1.1.2 *Methods for assessing remaining carbon budgets*

First, the basis for the median remaining carbon budget estimate is described based on MAGICC and FAIR non-CO_2 warming contributions. This is then compared to a simple analysis approach. Lastly, the uncertainty analysis is detailed.

2.SM.1.1.2.1 Median remaining carbon budget basis

This assessment employs historical net cumulative CO_2 emissions reported by the Global Carbon Project (Le Quéré et al., 2018). They report 2170±240 $GtCO_2$ emitted between 1 January 1876 and 31 December 2016. Annual CO_2 emissions for 2017 are estimated at about 41±4 $GtCO_2$/yr (Le Quéré et al., 2018) (Version 1.3 accessed 22 May 2018). From 1 Jan 2011 until 31 December 2017, an additional 290 $GtCO_2$ (270-310 $GtCO_2$, 1σ range) has been emitted (Le Quéré et al., 2018).

In WG1 AR5, TCRE was assessed to have a likely range of 0.22°C to 0.68°C per 1000 $GtCO_2$. The middle of this range (0.45°C per 1000 $GtCO_2$) is taken to be the best estimate, although no best estimate was explicitly defined (Collins et al., 2013; Stocker et al., 2013).

TCRE is diagnosed from integrations of climate models forced with CO_2 emissions only. However, also the influence of other climate forcers on global temperatures should also be taken into account (see Figure 3 in Knutti and Rogelj (2015).

The Reference Non-CO_2 Temperature Contribution (RNCTC) is defined as the median future warming due to non-CO_2 radiative forcing until the time of net-zero CO_2 emissions. The RNCTC is then removed from pre-defined levels of future peak warming (ΔT_{peak}) between 0.3 to 1.2 °C. The CO_2-only carbon budget is subsequently computed for this revised set of warming levels ($\Delta T_{\text{peak}} - RNCTC$).

In FAIR, the RNCTC is defined as the difference in temperature between two experiments, one where all anthropogenic emissions are included and one where only CO_2 emissions are included, using the constrained parameter set. Parallel integrations with matching physical parameters are performed for the suite of 205 scenarios in which CO_2 emissions become net zero during the 21st century. The non-CO_2 warming from a 2006-2015 average baseline is evaluated at the time in which CO_2 emissions become net zero. A linear regression between peak temperature relative to 2006-2015 and non-CO_2 warming relative to 2006-2015 at the time of net zero emissions is performed over the set of 205 scenarios (Figure 2.SM.4). The RNCTC acts to reduce the ΔT_{peak} by an amount of warming caused by non-CO_2 agents, which also takes into account warming effects of non-CO_2 forcing on the carbon-cycle response . In the MAGICC model the non-CO_2 temperature contribution is computed from the non-CO_2 effective radiative forcing time series for the same 205 scenarios, using the AR5 impulse response function (Myhre et al., 2013). As in FAIR, the RNCTC is then calculated from a linear regression of non-CO_2 temperature change against peak temperature.

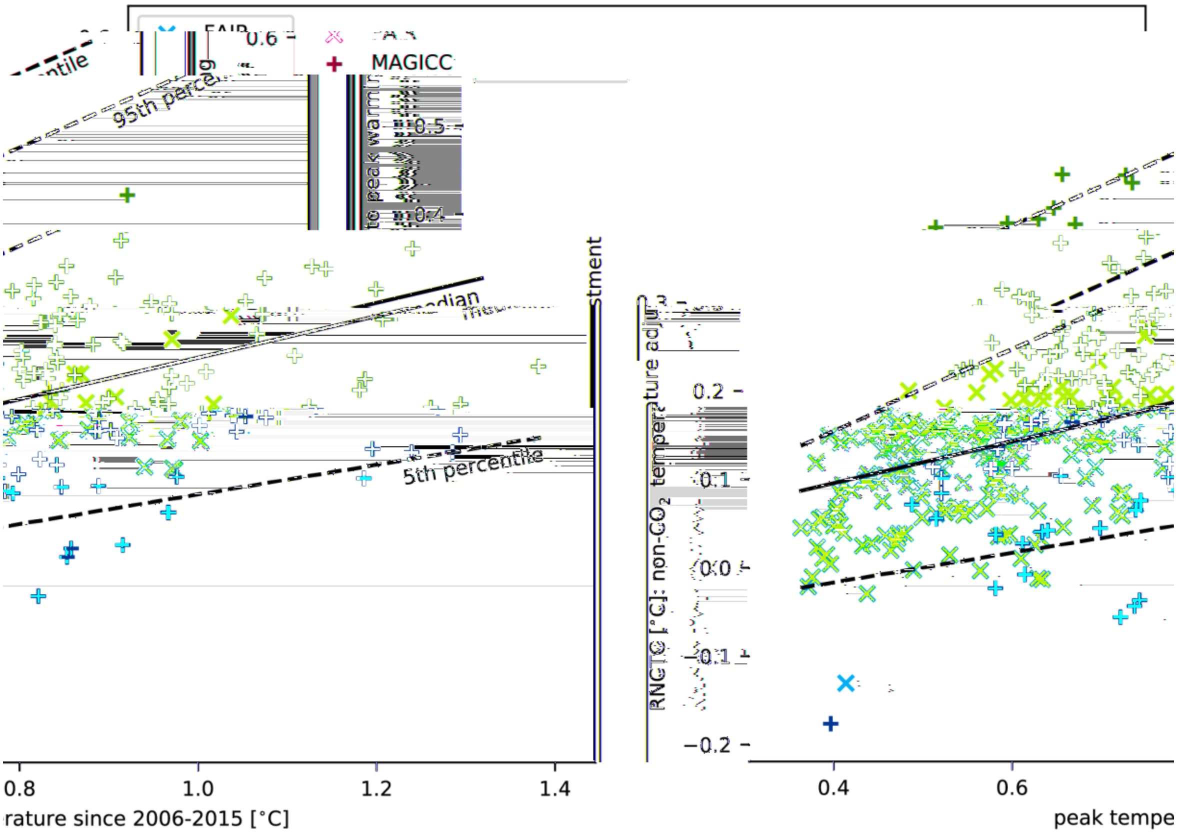


Figure 2.SM.4: Relationship of RNCTC with peak temperature in the FAIR and MAGICC models. The black line is the linear regression relationship between peak temperature and RNCTC. The dashed lines show the quantile regressions at the 5th and 95th percentile.

Table 2.SM.1 presents the CO_2 only budgets for different levels of future warming assuming both a normal and a log-normal TCRE distribution, where the overall distribution matches the AR5 *likely* TCRE range of 0.2° to 0.7°C per 1000 $GtCO_2$. Table 2.SM.2 presents the RNCTC values for different levels of future warming and how they affect the remaining carbon budget for the individual models assuming the normal distribution of TCRE. These are then averaged and rounded to give the numbers presented in the main chapter (Table 2.2). The budgets are taken with respect to the 2006–2015 baseline for temperature and 1 January 2018 for cumulative emissions. In the main report (Section 2.2), as well as in Table 2.SM.1, the estimates account for cumulative CO_2 emissions between the start of 2011 and the end of 2017 of about 290 $GtCO_2$.

Table 2.SM.1: Remaining carbon dioxide only budget in $GtCO_2$ from 1.1.2018 for different levels of warming from 2006–2015 for normal and log-normal distributions of TCRE based on the AR5 likely range. 290 $GtCO_2$ has been removed to account for emissions between the start of 2011 and the end of 2017. The assessed warming from 1850–1900 to 2006–2015 is about 0.87°C with 1-σ uncertainty range of ±0.12°C.

CO_2 only Remaining budgets ($GtCO_2$)	**Normal distribution**	**Log-normal distribution**

Table 2.SM.2: Remaining carbon dioxide budget from 1.1.2018 reduced by the effect of non-CO_2 forcers. Budgets are for different levels of warming from 2006–2015 for a normal distribution of TCRE based on the AR5 *likely* range of 0.2°C to 0.7°C per 1000 $GtCO_2$. 290 $GtCO_2$ has been removed to account for emissions between the start of 2011 and the end of 2017. This method employed the RNCTC estimates of non-CO_2 temperature change until the time of net zero CO_2 emissions.

Remaining carbon budgets ($GtCO_2$)	**MAGICC RNCTC**	**MAGICC**	**FAIR RNCTC**	**FAIR**

2.SM.1.1.2.2 Checks on approach

A simple approach to infer the carbon budget contribution from non-CO_2 forcers has been proposed based on global warming potential and is found to hold for a wide range of mitigation scenarios (Allen et al., 2018). This is based on an empirical relationship between peak temperature, TCRE, cumulative CO_2 emissions (G_{CO2}), non-CO_2 forcing ($\Delta F_{\text{non-CO2}}$) and the Absolute Global Warming Potential of CO_2 ($\text{AGWP}_H(\text{CO}_2)$) over time horizon H, taken to be 100 years:

$$\Delta T_{\text{peak}} \approx \text{TCRE} \times \left(G_{\text{CO2}} + \Delta F_{\text{non-CO2}} \times (H/\text{AGWP}_H(\text{CO}_2))\right) \qquad (1)$$

This method reduces the budget by an amount proportional to the change in non-CO_2 forcing. To determine this non-CO_2 forcing contribution, a Reference Non-CO_2 Forcing Contribution (RNCFC) is estimated from the MAGICC and FAIR runs. The RNCFC is defined as $\Delta F_{\text{non-CO2}}$ in eq. (1) which is a watts-per-metre-squared difference in the non-CO_2 effective radiative forcing between the 20 years before peak temperature is reached and 1996–2015. This provides an estimate of the non-CO_2 forcing contribution to the change in carbon budget. A similar calculation was performed for aerosol forcing in isolation (ΔF_{aer}) to show that the weakening aerosol forcing is the largest contributor to the smaller carbon budget, compared to the CO_2 only budget. AGWP_{100} values are taken from AR5 (Myhre et al., 2013) and the resultant remaining carbon budgets given in Table 2.SM.3. This method reduces the remaining carbon budget by 1091 $GtCO_2$ per Wm^{-2} of non-CO_2 effective radiative forcing (with a 5% to 95% range of 886 to 1474 $GtCO_2$). These results show good agreement to those computed with the RNCTC method from Table 2.SM.2, adding confidence to both methods. The RNCFC method is approximate and the choice of periods to use for averaging forcing is somewhat subjective, so the RNCTC is preferred over the RNCFC for this assessment.

Table 2.SM.3: Remaining carbon dioxide budgets from 1.1.2018 reduced by the effect of non-CO_2 forcers calculated by using a simple empirical approach based on non-CO_2 forcing (RNCFC) computed by the FAIR model. Budgets are for different levels of warming from 2006–2015 and for a normal distribution of TCRE based on the AR5 likely range of 0.2°C to 0.7°C per 1000 $GtCO_2$. 290 $GtCO_2$ has been removed to account for emissions between the start of 2011 and the end of 2017.

		FAIR
Remaining budgets ($GtCO_2$)	**FAIR RNCFC (**	

2.SM.1.1.2.3 Uncertainties

Uncertainties are explored across several lines of evidence and summarised in Table 2.2 of the main report. Expert judgement is both used to estimate an overall uncertainty estimate and the estimate to remove 100 $GtCO_2$ to account for possible missing permafrost and wetlands feedbacks (see Section 2.2). The uncertainty in the warming to the base period (1850–1900 to 2006–2015) estimated in Chapter 1 is 0.87°C with a ±0.12 °C *likely* (1-σ) range affects how close warming since preindustrial levels is to the 1.5°C and

2°C limits, so the remaining budgets for a range of future warming thresholds between 0.3 and 1.2 °C above present-day are analysed. The uncertainty in 2006–2015 warming compared to 1850–1900 relates to a ±250 $GtCO_2$ uncertainty in carbon budgets for a best estimate TCRE.

A measure of the uncertainty due to variations in the consistent level of non-CO_2 mitigation at the time net-zero CO_2 emissions are reached in pathways is analysed by a quantile regression of each pathway's median peak temperature against its corresponding median RNCTC (evaluated with the FAIR model), for the 5th, median and 95th percentiles of scenarios. A variation of approximately ±0.1°C around the median RNCTC is observed for median peak temperatures between 0.3 and 1.2°C above the 2006-2015 mean. This variation is equated to a ±250 $GtCO_2$ uncertainty in carbon budgets for a median TCRE estimate of about 0.45°C per 1000 $GtCO_2$. An uncertainty of -400 to +200 $GtCO_2$ is associated with the non-CO_2 forcing and response. This is analysed from a regression of 5th and 95th percentile RNCTC against 5th and 95th percentile peak temperature calculated with FAIR, compared to the median RNCTC response. These uncertainty contributions are shown in Table 2.2 in the main chapter

The effects of uncertainty in the TCRE distribution was gauged by repeating the remaining budget estimate for a log-normal distribution of the AR5 *likely* range. This reduces the median TCRE from 0.45 °C per 1000 $GtCO_2$ to 0.38°C per 1000 $GtCO_2$ (see Table 2.SM.1.1). Table 2.SM.1.4 presents these remaining budgets and shows that around 200 $GtCO_2$ would be added to the budget by assuming a log-normal *likely* range. The assessment and evidence supporting either distribution is discussed in the main chapter.

Table 2.SM.4: Remaining carbon dioxide budget from 1.1.2018 reduced by the effect of non-CO_2 forcers. Numbers are differences between estimates of the remaining budget made with the log-normal distribution compared to that estimated with a normal distribution of TCRE based on the AR5 *likely* range (see Table 2.SM.1). 290 $GtCO_2$ has been removed to account for emissions between the start of 2011 and the end of 2017. This method employed the FAIR model RNCTC estimates of non-CO_2 temperature response.

Remaining budgets ($GtCO_2$)	**Log-normal minus normal TCRE distribution**

Uncertainties in past CO_2 emissions ultimately impact estimates of the remaining carbon budgets for 1.5°C or 2°C. Uncertainty in CO_2 emissions induced by past land-use and land-cover changes contributes most, representing about 240 $GtCO_2$ from 1870 to 2017. Yet, this uncertainty is substantially reduced when deriving cumulative CO_2 emissions from a recent period. The cumulative emissions from the 2006–2015 reference period to 2017 used employed in this report are approximately 290 $GtCO_2$ with an uncertainty of about 20 $GtCO_2$.

2.SM.1.2 Integrated Assessment Models

The set of process-based integrated assessment models (IAMs) that provided input to this assessment is not fundamentally different from those underlying the IPCC AR5 assessment of transformation pathways (Clarke et al., 2014) and an overview of these integrated modelling tools can be found there. However, there have been a number of model developments since AR5, in particular improving the sectorial detail of IAMs (Edelenbosch et al., 2017b), the representation of solar and wind energy (Creutzig et al., 2017; Johnson et al., 2017; Luderer et al., 2017; Pietzcker et al., 2017), the description of bioenergy and food production and associated sustainability trade-offs (Havlík et al., 2014; Weindl et al., 2017; Bauer et al., 2018; Frank et al., 2018), the representation of a larger portfolio of carbon dioxide removal (CDR) technologies (Chen and Tavoni, 2013; Marcucci et al., 2017; Strefler et al., 2018b), the accounting of behavioural change (McCollum et al., 2016; van Sluisveld et al., 2016; van Vuuren et al., 2018) and energy demand developments (Edelenbosch et al., 2017a, c; Grubler et al., 2018), and the modelling of sustainable development implications (van Vuuren et al., 2015; Bertram et al., 2018), for example, relating to water use (Bonsch et al., 2014; Hejazi et al., 2014; Fricko et al., 2016; Mouratiadou et al., 2016, 2018), access to clean water and sanitation (Parkinson et al., 2017), materials use (Pauliuk et al., 2017), energy access (Cameron et al., 2016), air quality (Rao et al., 2017), and bioenergy use and food security (Frank et al., 2017; Humpenöder et al., 2018). Furthermore, since AR5, a harmonised model documentation of IAMs and underlying assumptions has been established within the framework of the EU ADVANCE project, and made available at http://www.fp7-advance.eu/content/model-documentation.

2.SM.1.2.1 Short introduction to the scope, use and limitations of integrated assessment modelling

IAMs are characterised by a dynamic representation of coupled systems, including energy, land, agricultural, economic and climate systems (Weyant, 2017). They are global in scope, and typically cover sufficient sectors and sources of greenhouse gas emissions to project anthropogenic emissions and climate change and identify consistency of different pathways with long-term goals of limiting warming to specific levels (Clarke et al., 2014). IAMs can be applied in a forward-looking manner to explore internally consistent socio-economic-climate futures, often extrapolating current trends under a range of assumptions or using counterfactual “no policy” assumptions to generate baselines for subsequent climate policy analysis. They can also be used in a back-casting mode to explore the implications of climate policy goals and climate targets for systems transitions and near-to-medium term action. In most IAM-based studies, both applications of IAMs are used concurrently (Clarke et al., 2009; Edenhofer et al., 2010; Luderer et al., 2012; Kriegler et al., 2014, 2015b, 2016; Riahi et al., 2015; Tavoni et al., 2015). Sometimes the class of IAMs is defined more narrowly as the subset of integrated pathway models with an economic core and equilibrium assumptions on supply and demand, although non-equilibrium approaches to integrated assessment modelling exist (Guivarch et al., 2011; Mercure et al., 2018). IAMs with an economic core describe consistent price-quantity relationships, where the “shadow price” of a commodity generally reflects its scarcity in the given setting. To this end, the price of greenhouse gas emissions emerging in IAMs reflects the restriction of future emissions imposed by a warming limit (Cross-chapter Box 5 in Chapter 2, Section 2.SM.1.2.2). Such price needs to be distinguished from suggested levels of emissions pricing in multi-dimensional policy contexts that are adapted to existing market environments and often include a portfolio of policy instruments (Section 2.5.2) (Stiglitz et al., 2017).

Detailed-process IAMs that describe energy-land transitions on a process level are critically different from stylized cost-benefit IAMs that aggregate such processes into stylized abatement cost and climate damage relationships to identify cost-optimal responses to climate change (Weyant, 2017). A key component of cost-benefit IAMs is the representation of climate damages which has been debated in the recent literature (Revesz et al., 2014; Cai et al., 2015; Lontzek et al., 2015; Burke et al., 2016; Stern, 2016). In the meantime, new approaches and estimates for improving the representation of climate damages are emerging (Dell et al., 2014; Burke et al., 2015, 2018; Hsiang et al., 2017) (Chapter 3 Box 3.6). A detailed discussion of the strengths and weaknesses of cost-benefit IAMs is provided in AR5 (Clarke et al., 2014; Kolstad et al., 2014; Kunreuther et al., 2014) (see also Cross-Chapter Box 5 in Chapter 2). The assessment of 1.5°C-consistent pathways in Chapter 2 relies entirely on detailed-process IAMs. These IAMs have so far rarely attempted a full representation of climate damages on socio-economic systems for mainly three reasons: a focus on the implications of mitigation goals for transition pathways (Clarke et al., 2014), the computational challenge to represent, estimate and integrate the complete range of climate impacts on a process level (Warszawski et al., 2014), and ongoing fundamental research on measuring the breadth and depth of how bio-physical climate impacts can affect societal welfare (Dennig et al., 2015; Adler et al., 2017; Hallegatte and Rozenberg, 2017). While some detailed-process IAMs account for climate impacts in selected sectors, e.g. agriculture (Stevanović et al., 2016), these IAMs do not take into account climate impacts as a whole in their pathway modelling. 1.5°C and 2°C-consistent pathways available to this report hence do not reflect climate impacts and adaptation challenges below 1.5°C and 2°C, respectively. Pathway modelling to date is also not able to identify socio-economic benefits of avoided climate damages between 1.5°C-consistent pathways and pathways leading to higher warming levels. These limitations are important knowledge gaps (Section 2.6) and subject of active research. Due to these limitations, the use of the integrated pathway literature in this report is concentrated on the assessment of mitigation action to limit warming to 1.5°C, while the assessment of impacts and adaptation challenges in 1.5°C warmer worlds relies on a different body of literature (see Chapters 3 to 5).

The use of IAMs for climate policy assessments has been framed in the context of solution-oriented assessments (Edenhofer and Kowarsch, 2015; Beck and Mahony, 2017). This approach emphasizes the exploratory nature of integrated assessment modelling to produce scenarios of internally consistent, goal-oriented futures. They describe a range of pathways that achieve long-term policy goals, and at the same time highlight trade-offs and opportunities associated with different courses of action. This literature has noted, however, that such exploratory knowledge generation about future pathways cannot be completely isolated from societal discourse, value formation and decision making and therefore needs to be reflective of its performative character (Edenhofer and Kowarsch, 2015; Beck and Mahony, 2017). This suggests an interactive approach which engages societal values and user perspectives in the pathway production process. It also requires transparent documentation of IAM frameworks and applications to enable users to contextualize pathway results in the assessment process. Integrated assessment modelling results assessed in AR5 were documented in Annex II of AR5 (Krey et al., 2014b), and this Annex aims to document the IAM frameworks that fed into the assessment of 1.5°C-consistent pathways in Chapter 2 of this report. It draws upon increased efforts to extend and harmonize IAM documentations[1] (Section 2.SM.1.2.5). Another important aspect for the use of IAMs in solution-oriented assessments is trust building in their applicability and validity. The literature has discussed approaches to IAM evaluation (Schwanitz, 2013; Wilson et al., 2017), including model diagnostics (Kriegler et al., 2015a; Wilkerson et al., 2015; Craxton et al., 2017) and comparison with historical developments (Wilson et al., 2013; van Sluisveld et al., 2015).

2.SM.1.2.2 Economics and Policy Assumptions in IAMs

Experiments with IAMs most often create scenarios under idealised policy conditions which assume that climate change mitigation measures are undertaken where and when they are the most effective (Clarke et al., 2014). Such 'idealised implementation' scenarios assume that a global price on GHG emissions is implemented across all countries, all economic sectors, and rises over time through 2100 in a way that will minimise discounted economic costs. The emissions price reflects marginal abatement costs and is often used as a proxy of climate policy costs (see Section 2.5.2). Scenarios developed under these assumptions are often referred to as 'least-cost' or 'cost-effective' scenarios because they result in the lowest aggregate global mitigation costs when assuming that global markets and economies operate in a frictionless, idealised way (Clarke et al., 2014; Krey et al., 2014b). However, in practice, the feasibility (see Cross-Chapter Box 3 in Chapter 1) of a global carbon pricing mechanism deserves careful consideration (see Chapter 4.4). Scenarios from idealised conditions provide benchmarks for policy makers, since deviations from the idealized approaches capture important challenges for socio-technical and economic systems and resulting climate outcomes.

Model experiments diverging from idealised policy assumptions aim to explore the influence of policy barriers to implementation of globally cost-effective climate change mitigation, particularly in the near term. Such scenarios are often referred to as 'second-best' scenarios. They include, for instance, (i) fragmented

---

[1] FOOTNOTE: http://www.fp7-advance.eu/content/model-documentation

policy regimes in which some regions champion immediate climate mitigation action (e.g. 2020) while other regions join this effort with a delay of one or more decades (Clarke et al., 2009; Blanford et al., 2014; Kriegler et al., 2015b), (ii) prescribed near-term mitigation efforts (until 2020 or 2030) after which a global climate target is adopted (Luderer et al., 2013, 2016; Rogelj et al., 2013b; Riahi et al., 2015), or (iii) variations in technology preferences in mitigation portfolios (Edenhofer et al., 2010; Luderer et al., 2012; Tavoni et al., 2012; Krey et al., 2014a; Kriegler et al., 2014; Riahi et al., 2015; Bauer et al., 2017, 2018). Energy transition governance adds a further layer of potential deviations from cost-effective mitigation pathways and has been shown to lead to potentially different mitigation outcomes (Trutnevyte et al., 2015; Chilvers et al., 2017; Li and Strachan, 2017). Governance factors are usually not explicitly accounted for in IAMs.

Pricing mechanisms in IAMs are often augmented by assumptions about regulatory and behavioural climate policies in the near- to mid-term (Bertram et al., 2015; van Sluisveld et al., 2016; Kriegler et al., 2018). The choice of GHG price trajectory to achieve a pre-defined climate goal varies across IAMs and can affect the shape of mitigation pathways. For example, assuming exponentially increasing CO_2 pricing to stay within a limited CO_2 emissions budget is consistent with efficiency considerations in an idealized economic setting, but can lead to temporary overshoot of the carbon budget if carbon dioxide removal (CDR technologies) are available. The pricing of non-CO_2 greenhouse gases is often pegged to CO_2 pricing using their global warming potentials (mostly GWP_{100}) as exchange rates (see Cross-Chapter Box 2 in Chapter 1). This leads to stringent abatement of non-CO_2 gases in the medium- to long-term, but also incentivizes continued compensation of these gases by CDR even after their full abatement potential is exploited, thus contributing to the pattern of peaking and declining temperatures in many mitigation pathways.

The choice of economic discount rate is usually reflected in the increase of GHG pricing over time and thus also affects the timing of emissions reductions. For example, the deployment of capital-intensive abatement options like renewable energy can be pushed back by higher discount rates. IAMs make different assumptions about the discount rate, with many of them assuming a social discount rate of ca. 5% per year (Clarke et al., 2014). In a survey of modelling teams contributing scenarios to the database for this assessment, discount rate assumptions varied between 2%/year and 8%/year depending on whether social welfare considerations or the representation of market actor behaviour is given larger weight. Some IAMs assume fixed charge rates that can vary by sector taking into account that private actors require shorter time horizons to amortize their investment. The impact of the choice of discount rate on mitigation pathways is underexplored in the literature. In general, the choice of discount rate is expected to have smaller influence on low-carbon technology deployment schedules for tighter climate targets as they leave less flexibility in the timing of emissions reductions. However, the introduction of large-scale CDR options might increase sensitivity again. It was shown, for example, that if a long-term CDR option like direct air capture with CCS (DACCS) is introduced in the mitigation portfolio, lower discount rates lead to more early abatement and less CDR deployment (Chen and Tavoni, 2013). If discount rates vary across regions, with higher costs of capital in developing countries, industrialized countries mitigate more and developing countries less at higher overall mitigation costs compared to a case with globally uniform discounting (Iyer et al., 2015). More work is needed to study the sensitivity of the deployment schedule of low-carbon technologies to the choice of the discount rate. However, as overall emissions reductions need to remain consistent with the choice of climate goal, mitigation pathways from detailed process-based IAMs are still less sensitive to the choice of discount rate than cost-optimal pathways from cost-benefit IAMs (see Box 6.1 in Clarke et al., 2014) which have to balance near-term mitigation with long-term climate damages across time (Nordhaus, 2005; Dietz and Stern, 2008; Kolstad et al., 2014; Pizer et al., 2014) (see Cross-Chapter Box 5 in Chapter 2).

2.SM.1.2.3 Technology assumptions and transformation modelling

Although model-based assessments project drastic near, medium and long-term transformations in 1.5°C scenarios, projections also often struggle to capture a number of hallmarks of transformative change, including disruption, innovation, and nonlinear change in human behaviour (Rockström et al., 2017). Regular revisions and adjustments are standard for expert and model projections, for example, to account for new information such as the adoption of the Paris Agreement. Costs and deployment of mitigation technologies will differ in reality from the values assumed in the full-century trajectories of the model results. CCS and nuclear provide examples of where real-world costs have been higher than anticipated (Grubler, 2010; Rubin et al., 2015) while solar PV is an example where real-world costs have been lower (Creutzig et al., 2017; Figueres et al., 2017; Haegel et al., 2017). Such developments will affect the low-carbon transition for achieving stringent mitigation targets. This shows the difficulty of adequately estimating social and technological transitions and illustrates the challenges of producing scenarios consistent with a quickly evolving market (Sussams and Leaton, 2017).

Behavioural and institutional frameworks affect the market uptake of mitigation technologies and socio-technical transitions (see Chapter 4.4). These aspects co-evolve with technology change and determine, among others, the adoption and use of low-carbon technologies (Clarke et al., 2014), which in turn can affect both the design and performance of policies (Kolstad et al., 2014; Wong-Parodi et al., 2016). Pre-determining technological change in models can preclude the examination of policies that aim to promote disruptive technologies (Stanton et al., 2009). In addition, knowledge creation, networks, business strategies, transaction costs, microeconomic decision-making processes and institutional capacities influence (no-regret) actions, policy portfolios and innovation processes (and vice versa) (Mundaca et al., 2013; Lucon et al., 2014; Patt, 2015; Wong-Parodi et al., 2016; Geels et al., 2017); however, they are difficult to capture in equilibrium or cost-minimisation model-based frameworks (Laitner et al., 2000; Wilson and Dowlatabadi, 2007; Ackerman et al., 2009; Ürge-Vorsatz et al., 2009; Mundaca et al., 2010; Patt et al., 2010; Brunner and Enting, 2014; Grubb et al., 2014; Patt, 2015; Turnheim et al., 2015; Geels et al., 2017; Rockström et al., 2017). It is argued that assessments that consider greater end-user heterogeneity, realistic market behaviour, and end-use technology details can address a more realistic and varied mix of policy instruments, innovation processes and transitional pathways (Ürge-Vorsatz et al., 2009; Mundaca et al., 2010; Wilson et al., 2012; Lucon et al., 2014; Li et al., 2015; Trutnevyte et al., 2015; McCollum et al., 2016; Geels et al., 2017). So-called 'rebound' effects in which behavioural changes partially offset policies, such as consumers putting less effort into demand reduction when efficiency is improved, are captured to a varying and in many cases only limited degree in IAMs.

There are also substantial variation in mitigation options represented in IAMs (see Section 2.SM.1.2.6) which depend, on the one hand, on the constraints of individual modelling frameworks and on the other hand on model development decisions influenced by modellers' beliefs and preferences (Section 2.3.1.2). Further limitations can arise on the system level. For example, trade-offs between material use for energy versus other uses are not fully captured in many IAMs (e.g. petroleum for plastics, biomass for material substitution). An important consideration for the analysis of mitigation potential is the choice of baseline. For example, IAMs often assume, in line with historical experience, that economic growth leads to a reduction in local air pollution as populations become richer (i.e. an environmental Kuznets curve) (Rao et al., 2017). In such cases, the mitigation potential is small because reference emissions that take into account this economic development effect are already low in scenarios that see continued economic development over their modelling time horizon. Assumptions about reference emissions are important because high reference emissions lead to high perceived mitigation potentials and potential overestimates of the actual benefit, while low reference emissions lead to low perceived benefits of mitigation measures and thus less incentive to address these important climate and air pollutants (Gschrey et al., 2011; Shindell et al., 2012; Amann et al., 2013; Rogelj et al., 2014; Shah et al., 2015; Velders et al., 2015).

2.SM.1.2.4 Land use and bioenergy modelling in IAMs

The IAMs used in the land use assessment in this chapter and that are based on the SSPs (Popp et al., 2017; Riahi et al., 2017) all include an explicit land model.[2] These land models calculate the supply of food, feed, fiber, forestry, and bioenergy products (see also Chapter 2 Box 2.1). The supply depends on the amount of land allocated to the particular good, as well as the yield for the good. Different IAMs have different means of calculating land allocation and different assumptions about yield, which is typically assumed to increase

---

FOOTNOTE: There are other IAMs that do not include an explicit land use representation. These models use supply curves to represent bioenergy; that is, they have an exogenously specified relationship between the quantity of bioenergy supplied and the price of bioenergy. These models include land use change emissions in a similar manner, with the amount of emissions depending on the amount of bioenergy supplied. For some of these models, LUC emissions are assumed to be zero, regardless of the amount of bioenergy.

over time reflecting technological progress in the agricultural sector (see (Popp et al., 2014) for examples). In these models, the supply of bioenergy (including BECCS) depends on the price and yield of bioenergy, the policy environment (e.g., any taxes or subsidizes affecting bioenergy profits), as well the demand for land for other purposes. Dominant bioenergy feedstocks assumed in IAMs are woody and grassy energy crops (2nd generation biomass) in addition to residues. Some models implement a "food first" approach, where food demands are met before any land is allocated to bioenergy. Other models use an economic land allocation approach, where bioenergy competes with other land uses depending on profitability. Competition between land uses depend strongly on socio-economic drivers such as population growth and food demand, and are typically varied across scenarios. When comparing global bioenergy yields from IAMs with the bottom-up literature, care must be taken that assumptions are comparable. An in-depth assessment of the land-use components of IAMs is outside the scope of this Special Report.

In all IAMs that include a land model, the land-use change emissions associated with these changes in land allocation are explicitly calculated. Most IAMs use an accounting approach to calculating land use change emissions, similar to Houghton (Houghton et al., 2012). These models calculate the difference in carbon content of land due to the conversion from one type to another, and then allocate that difference across time in some manner. For example, increases in forest cover will increase terrestrial carbon stock, but that increase may take decades to accumulate. If forestland is converted to bioenergy, however, those emissions will enter the atmosphere more quickly.

IAMs often account for carbon flows and trade flows related to bioenergy separately. That is, IAMs may treat bioenergy as "carbon neutral" in the energy system, in that the carbon price does not affect the cost of bioenergy. However, these models will account for any land-use change emissions associated with the land conversions needed to produce bioenergy. Additionally, some models will separately track the carbon uptake from growing bioenergy and the emissions from combusting bioenergy (assuming it is not combined with CCS).

Table 2.SM.5: Land-use types descriptions as reported in pathways (adapted from the SSP database: https://tntcat.iiasa.ac.at/SspDb/)

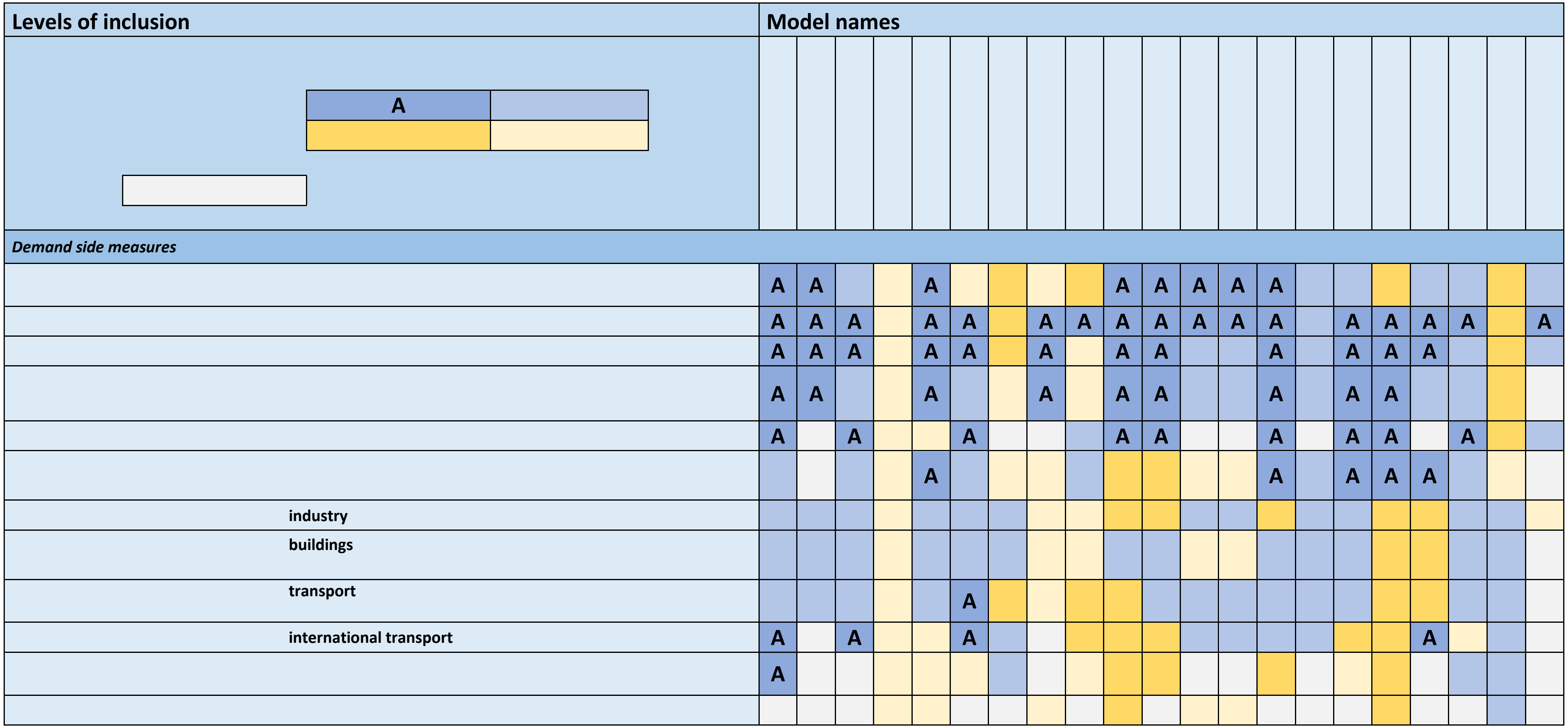
Land use type	**Description/examples**
Energy crops	Land dedicated to second generation energy crops. (e.g., switchgrass, miscanthus, fast-growing wood species)
Other crops	Food and feed/fodder crops
Pasture	Pasture land. All categories of pasture land - not only high quality rangeland. Based on FAO definition of "permanent meadows and pastures"
Managed forest	Managed forests producing commercial wood supply for timber or energy but also afforestation (note: woody energy crops are reported under "energy crops")
Natural forest	Undisturbed natural forests, modified natural forests and regrown secondary forests
Other natural land	Unmanaged land (e.g., grassland, savannah, shrubland, rock ice, desert), excluding forests

2.SM.1.2.5 Contributing modelling framework reference cards

For each of the contributing modelling frameworks a reference card has been created highlighting the key features of the model. These reference cards are either based on information received from contributing modelling teams upon submission of scenarios to the SR1.5 database, or alternatively drawn from the ADVANCE IAM wiki documentation, available at http://www.fp7-advance.eu/content/model-documentation, and updated. These reference cards are provided in part 2 of this Supplementary Material.

2.SM.1.2.6 Overview mitigation measures in contributed IAM scenarios

Table 2.SM.6: Overview of representation of mitigation measures in the integrated pathway literature, as submitted to the database supporting this report. Levels of inclusion have been elicited directly from contributing modelling teams by means of a questionnaire. The table shows the reported data. Dimensions of inclusion are explicit versus implicit, and endogenous or exogenous. An implicit level of inclusion is assigned when a mitigation measure is represented by a proxy like a marginal abatement cost curve in the AFOLU sector without modelling individual technologies or activities. An exogenous level of inclusion is assigned when a mitigation measure is not part of the dynamics of the modelling framework but can be explored through alternative scenarios.



A	🟦
🟧	🟨

⬜

Levels of inclusion	Model names																				
Demand side measures																					
	A	A	🟦	🟨	A	🟨	🟧	🟨	🟧	A	A	A	A	A	🟦	🟦	🟧	🟦	🟦	🟧	🟦
	A	A	A	🟨	A	A	🟧	A	A	A	A	A	A	A	🟦	A	A	A	A	🟧	A
	A	A	A	🟨	A	A	🟧	A	🟨	A	A	🟦	🟦	A	🟦	A	A	A	🟦	🟧	🟦
	A	A	🟦	🟨	A	🟦	🟨	A	🟨	A	A	🟦	🟦	A	🟦	A	A	🟦	🟦	🟧	⬜
	A	⬜	A	🟨	🟨	A	⬜	⬜	🟦	A	A	⬜	⬜	A	⬜	A	A	⬜	A	🟧	🟦
	🟦	⬜	🟦	🟨	A	🟦	🟨	🟨	🟦	🟧	🟧	🟨	🟨	A	🟦	A	A	A	🟦	🟨	⬜
industry	🟦	🟦	🟦	🟨	🟦	🟦	🟦	🟨	🟨	🟧	🟧	🟦	🟦	🟧	🟦	🟦	🟧	🟧	🟦	🟦	🟨
buildings	🟦	🟦	🟦	🟨	🟦	🟦	🟦	🟨	🟨	🟦	🟦	🟨	🟨	🟦	🟦	🟦	🟧	🟧	🟦	🟦	⬜
transport	🟦	🟦	🟦	🟨	🟦	A	🟧	🟨	🟧	🟧	🟦	🟦	🟦	🟦	🟦	🟦	🟧	🟧	🟦	🟦	⬜
international transport	A	⬜	A	🟨	🟨	A	🟦	⬜	🟧	🟧	🟧	🟦	🟦	🟦	🟦	🟧	🟧	A	🟨	🟦	⬜
	A	⬜	⬜	🟨	🟨	🟨	🟦	⬜	🟨	🟧	🟧	⬜	⬜	🟧	⬜	🟨	🟧	⬜	🟦	🟦	⬜
	⬜	⬜	⬜	🟨	🟨	⬜	⬜	🟨	⬜	🟧	⬜	🟨	🟨	⬜	⬜	⬜	🟧	⬜	⬜	🟦	⬜

Levels of inclusion	Model names																				
A																					
		A	A					A	A	A	A			A		A	A				A
	A					A															
Supply side measures																					
Decarbonisation of electricity:																					
	A	A	A		A	A		A	A	A	A	A	A	A	A	A	A	A	A	A	A
			A			A		A		A	A	A	A	A	A	A	A	A	A	A	A
	A	A	A		A	A		A	A	A	A	A	A	A	A	A	A	A	A	A	A
	A	A	A		A	A		A	A	A	A	A	A		A	A	A	A	A	A	A
	A	A	A		A	A		A	A	A	A	A	A	A	A	A	A	A	A	A	A
	A	A	A		A	A		A	A	A	A	A	A	A	A	A	A	A	A	A	A
			A			A									A						
			A		A	A		A	A	A	A			A	A	A	A	A	A	A	A
	A	A	A		A	A			A	A	A	A	A	A	A	A		A	A		A
								A		A	A							A		A	
	A		A		A	A			A	A	A					A	A	A			
Decarbonisation of non-electric fuels:																					
		A	A		A	A		A	A	A				A	A	A	A	A	A	A	
	A		A		A	A			A	A	A		A	A	A			A		A	A
	A	A	A		A	A		A	A	A	A		A	A	A	A	A	A	A	A	A
			A																	A	
			A		A			A							A	A	A				
			A					A		A	A					A	A	A	A	A	

A	

Levels of inclusion	**Model names**																				
									A	A					A	A					
Other processes:																					
	A	A			A	A		A	A	A	A			A		A	A	A	A	A	
														A		A	A	A			
			A								A							A			
					A																
					A					A	A							A	A		
			A		A			A		A						A	A	A	A		
AFOLU measures																					
	A		A			A										A	A				
																A	A				
																A	A				
	A		A		A								A			A	A		A		
																A	A				
													A			A	A				
													A			A	A				
																A	A				
Carbon dioxide (greenhouse gas) removal																					

Levels of inclusion	**Model names**																				
	A	A	A		A	A			A	A	A	A	A	A	A	A		A	A		A
															A				A		
	A		A		A	A			A							A	A		A		A
																A	A				
										A				A						A	

2.SM.1.3 Overview of SR1.5 scenario database collected for the assessment in the Chapter

The scenario ensemble collected in the context of this report represents an ensemble of opportunity based on available published studies. The submitted scenarios cover a wide range of scenario types and thus allow exploration of a wide range of questions. For this to be possible, however, critical scenario selection based on scenario assumptions and setup is required. For example, as part of the SSP framework, a structured exploration of 1.5°C pathways was carried out under different future socioeconomic developments (Rogelj et al., 2018). This allows to determine the fraction of successful (feasible) scenarios per SSPs (Table 2.SM.7), an assessment which cannot be carried out with a more arbitrary ensemble of opportunity.

Table 2.SM.7: Summary of models (with scenarios in the database) attempting to create scenarios with an end-of-century forcing of 1.9W m^{-2}, consistent with limiting warming to below 1.5°C in 2100, and related SPAs. Notes: 1= successful scenario consistent with modelling protocol; 0= unsuccessful scenario; x= not modelled; 0*= not attempted because scenarios for a 2.6 W m^{-2} target were already found to be unachievable in an earlier study. SSP3-SPA3for a more stringent 1.9 W m^{-2} radiative forcing target has thus not been attempted anew by many modelling teams. Marker implementations for all forcing targets within each SSP are indicated in blue. Source: (Rogelj et al., 2018).

Model	Methodology	Reported scenario				

2.SM.1.3.1 Configuration of SR1.5 scenario database

The Integrated Assessment Modelling Consortium (IAMC), as part of its ongoing cooperation with Working Group III of the IPCC, issued a call for submissions of scenarios of 1.5°C global warming and related scenarios to facilitate the assessment of mitigation pathways in this special report. This database is hosted by the International Institute for Applied Systems Analysis (IIASA) at http://data.ene.iiasa.ac.at/sr1p5/. Upon approval of this report, the database of scenarios underlying this assessment will also be published. Computer scripts and tools used to conduct the analysis and generate figures are also available for download from that website.

2.SM.1.3.1.1 Criteria for submission to the scenario database

Scenarios submitted to the database were required to either aim at limiting warming to 1.5°C or 2°C in the long term, or to provide context for such scenarios, for example, corresponding NDC and baseline scenarios without climate policy. Model results should constitute an emissions trajectory over time with underlying socio-economic development until at least the year 2050 generated by a formal model such as a dynamic systems, energy-economy, partial or general equilibrium or integrated assessment model.

The end of the 21st century is referred to as "long term" in the context of this scenario compilation. For models with time horizons shorter than 2100, authors and/or submitting modelling teams were asked to explain how they evaluated their scenario as being consistent with 1.5°C in the long term. Ultimately, scenarios that only covered part of the 21st century could only to a very limited degree be integrated in the assessment, as the longer-term perspective was lacking. Submissions of emissions scenarios for individual regions and specific sectors were possible, but no such scenarios were received.

Each scenario submission required a supporting publication in a peer-reviewed journal that was accepted until 15 May 2018. Alternatively, the scenario must have been published by the same date in a report that has been determined by IPCC to be eligible grey literature (see Table 2.SM.9). As part of the submission process, the authors of the underlying modelling team agreed to the publication of their model results in this scenario database.

2.SM.1.3.1.2 Historical consistency analysis of submitted scenarios

Submissions to the scenario database were compared to the following data sources for historical periods to identify reporting issues.

Historical emissions database (CEDS)
Historical emissions imported from the *Community Emissions Data System (CEDS) for Historical Emissions* (http://www.globalchange.umd.edu/ceds/) have been used as a reference and for use in figures (van Marle et al., 2017; Hoesly et al., 2018). Historical N_2O emissions, which are not included in the CEDS database, are compared against the RCP database (http://tntcat.iiasa.ac.at/RcpDb/).

Historical IEA World Energy Balances and Statistics
Aggregated historical time series of the energy system from the IEA World Energy Balances and Statistics (revision 2017) were used as a reference for validation of submitted scenarios and for use in figures.

2.SM.1.3.1.3 Verification of completeness and harmonization for climate impact assessment

Categorizing scenarios according to their long-term warming impact requires reported emissions time series until the end of the century of the following species: CO_2 from energy and industrial processes, methane, nitrous oxide and sulphur. The long-term climate impact could not be assessed for scenarios not reporting these species, and these scenarios were hence not included in any subsequent analysis.

For the diagnostic assessment of the climate impact of each submitted scenario, reported emissions were harmonized to historical values (base year 2010) as provided in the RCP database by applying an additive offset, which linearly decreased until 2050. For non-CO_2 emissions where this method resulted in negative values, a multiplicative offset was used instead. Emissions other than the required species that were not reported explicitly in the submitted scenario were filled from RCP2.6 (Meinshausen et al., 2011b; van Vuuren et al., 2011) to provide complete emissions profiles to MAGICC and FAIR (see section 2.SM.1.1).

The harmonization and completion of non-reported emissions was only applied to the diagnostic assessment as input for the climate impact using MAGICC and FAIR. All figures and analysis used in the chapter analysis are based on emissions as reported by the modelling teams, except for column "cumulative CO_2 emissions, harmonized" in Table 2.SM.12.

2.SM.1.3.1.4 Validity assessment of historical emissions for aggregate Kyoto greenhouse gases

The AR5 WGIII report assessed Kyoto greenhouse gases (GHG) in 2010 to fall in the range of 44.5-53.5 $GtCO_2e$/yr using the GWP_{100}-metric from the IPCC Second Assessment Report. As part of the diagnostics, the Kyoto GHG aggregation was recomputed using GWP_{100} according to SAR, AR4 and AR5 for all scenarios that provided sufficient level of detail for their emissions. A total of 33 scenarios from three modelling frameworks showed recomputed Kyoto GHG outside the year-2010 range assessed by the AR5 WGIII report. These scenarios were excluded from all analysis of near-term emissions evolutions, in particular in Figures 2.6, 2.7 and 2.8, and Table 2.4.

2.SM.1.3.1.5 Plausibility assessment of near-term development

Submitted scenarios were assessed for the plausibility of their near-term development across a number of dimensions. One issue identified were drastic reductions of CO_2 emissions from the land-use sector already in 2020. Given recent trends, this was considered implausible and all scenarios from the ADVANCE and EMF33 studies reporting negative CO_2 emissions from the land-use sector in 2020 were excluded from the analysis throughout this chapter.

2.SM.1.3.1.6 Missing carbon price information

Out of the 132 scenarios limiting global warming to 2°C throughout the century (see Table 2.SM.8), a total of twelve scenarios submitted by three modelling teams reported carbon prices of 0 or missing values in at least one year. These scenarios were excluded from the analysis.in Section 2.5 and Figure 2.26 in the chapter.

2.SM.1.3.2 Contributions to the SR1.5 database by modelling framework

In total, 19 modelling frameworks submitted 529 individual scenarios based manuscripts that were published or accepted for publication by 15 May 2018 (Table 2.SM.8).

Table 2.SM.8: Overview of submitted scenarios by modelling framework, including the categorization according to the climate impact (cf. Section 2.SM.1.4) and outcomes of validity and near-term plausibility assessment of pathways (cf. Section 2.SM.1.3.1).

	Below-1.5°C	**1.5°C return with low OS**	**1.5°C return with high OS**	**Lower 2°C**	**Higher 2°C**	**Above 2°C**	**Scenarios assessed**	**Not full century**	**Missing emissions species for assessment**	**Negative CO^2 emissions (AFOLU) in 2020**	**Scenarios submitted**
AIM		6	1	24	10	49	**90**				**90**
BET									16		**16**
C-ROADS	2	1	2			1	**6**				**6**
DNE21+									21		**21**
FARM									13		**13**
GCAM		1	2	1	3	16	**23**			24	**47**
GEM-E3								4			**4**
GENeSYS-MOD								1			**1**
GRAPE									18		**18**
IEA ETP								1			**1**
IEA World Energy Model					1		**1**				**1**
IMACLIM								7	12		**19**
IMAGE		7	4	6	9	35	**61**				**61**
MERGE		1			1	1	**3**				**3**
MESSAGE		6	6	11	13	22	**58**				**58**
POLES	4	7	5	9	3	9	**37**				**37**
REMIND	2	11	17	16	16	31	**93**				**93**
Shell World Energy Model								1			**1**
WITCH	1	4		7	2	25	**39**				**39**
Total	**9**	**44**	**37**	**74**	**58**	**189**	**411**	**14**	**80**	**24**	**529**

2.SM.1.3.3 Overview and scope of studies available in SR1.5 database

Table 2.SM.9: Recent studies included in the scenario database that this chapter draws upon and their key foci indicating which questions can be explored by the scenarios of each study. The difference between "Scenarios submitted" and "Scenarios assessed" is due to criteria described in Section 2.SM.1.3.1. The numbers between brackets indicate the modelling frameworks assessed.

Study/model name	**Key focus**	**Reference papers**	**Modelling frameworks**	**Scenarios submitted**	**Scenarios assessed**
Multi-model studies					
SSPx-1.9	Development of new community scenarios based on the full SSP framework limiting end-of-century radiative forcing to 1.9 W m$^{-2.}$	Riahi et al. (2017) Rogelj et al. (2018)	6	126	126
ADVANCE	Aggregate effect of the INDCs, comparison to optimal 2°C/1.5°C scenarios ratcheting up after 2020. Decarbonisation bottlenecks and the effects of following the INDCs until 2030 as opposed to ratcheting up to optimal ambition levels after 2020 in terms of additional emissions locked in. Constraint of 400 $GtCO_2$ emissions from energy and industry over 2011-2100.	Vrontisi et al. (2018) Luderer et al. (2018)	9 (6)	74	55
CD-LINKS	Exploring interactions between climate and sustainable development policies with the aim to identify robust integral policy packages to achieve all objectives. Evaluating implications of short-term policies on the mid-century transition in 1.5°C pathways linking the national to the global scale. Constraint of 400 $GtCO_2$ emissions over 2011-2100.	McCollum et al. (2018)	8 (6)	36	36
EMF-33	Study of the bioenergy contribution in deep mitigation scenarios. Constraint of 400 $GtCO_2$ emissions from energy and industry over 2011-2100.	Bauer et al. (2018)	11 (5)	183	86
Single-model studies					
IMAGE 1.5	Understanding the dependency of 1.5°C pathways on negative emissions.	van Vuuren et al. (2018)		8	8
IIASA LED (MESSAGEix)	A global scenario of Low Energy Demand (LED) for Sustainable Development below 1.5°C without Negative Emission Technologies.	Grubler et al. (2018)		1	1
GENeSYS-MOD	Application of the Open-Source Energy Modelling System to the question of 1.5°C and 2°C pathways.	Löffler et al. (2017)		1	0
IEA WEO	World Energy Outlook.	OECD/IEA and IRENA (2017)		1	1
OECD/IEA ETP	Energy Technology Perspectives.	IEA (2017)		1	0
PIK CEMICS (REMIND)	Study of CDR requirements and portfolios in 1.5°C pathways.	Strefler et al. (2018a)		7	7
PIK PEP (REMIND-MAgPIE)	Exploring short-term policies as entry points to global 1.5°C pathways.	Kriegler et al. (2018)		13	13
PIK SD (REMIND-MAgPIE)	Targeted policies to compensate risk to sustainable development in 1.5°C scenarios.	Bertram et al. (2018)		12	12
AIM SFCM	Socio-economic factors and future challenges of the goal of limiting the increase in global average temperature to 1.5°C.	Liu et al. (2017)		33	33
C-Roads	Interactions between emissions reductions and carbon dioxide removal.	Holz et al. (2018)		6	6
PIK EMC		Luderer et al. (2013)		8	8
MESSAGE GEA		Rogelj et al. (2013a, 2013b, 2015)		10	10
AIM TERL	The contribution of transport policies to the mitigation potential and cost of 2 °C and 1.5 °C goals	Zhang et al. (2018)		6	6
MERGE-ETL	The role of Direct Air Capture and Storage (DACS) in 1.5°C pathways.	Marcucci et al. (2017)		3	3
Shell SKY	A technically possible, but challenging pathway for society to achieve the goals of the Paris Agreement.	Shell International B.V. (2018)		1	0

2.SM.1.3.4 Data collected

A reporting template was developed to facilitate the collection of standardized scenario results. The template was structured in nine categories, and each category was divided into four priority levels: “Mandatory”, “High priority (Tier 1)”, “Medium priority (Tier 2)”, and “Other”. In addition, one category was included to collect input assumptions on capital costs to facilitate the comparison across engineering-based models. An overview and definitions of all variables will be made available as part of the database publication.

Table 2.SM.10: Number of variables (time series of scenario results) per category and priority level.

Category	**Description**	**Mandatory (Tier 0)**	**High priority (Tier 1)**	**Medium priority (Tier 2)**	**Other**	**Total**
Energy	Configuration of the energy system (for the full conversion chain of energy supply from primary energy extraction, electricity capacity, to final energy use)	19	91	83	0	193
Investment	Energy system investment expenditure	0	4	22	17	43
Emissions	Emissions by species and source	4	19	55	25	103
CCS	Carbon capture and sequestration	3	10	11	8	32
Climate	Radiative forcing and warming	0	11	2	8	21
Economy	GDP, prices, policy costs	2	15	25	7	49
SDG	Indicators on sustainable development goals achievement	1	9	11	1	22
Land	Agricultural production & demand	0	14	10	5	29
Water	Water consumption & withdrawal	0	0	16	1	17
Capital costs	Major electricity generation and other energy conversion technologies	0	0	0	31	31
Total		**29**	**173**	**235**	**103**	**540**

2.SM.1.4 Scenario classification

A total of 529 scenarios were submitted to the scenario database. Of these, 14 scenarios did not report results until the end of the century and an additional 80 scenarios did not report the required emissions species. During the validation and diagnostics, 24 scenarios were excluded because of negative CO_2 emissions from the land-use sector by 2020 (see Section 2.SM.1.3). Therefore, the analysis in this report is based on 411 scenarios, of which 90 scenarios are consistent with 1.5°C at the end of the century and 132 remain below 2°C throughout the century (not including the 90 scenarios that are deemed consistent with 1.5°C). Table 2.SM.11 provides an overview of the number of scenarios per class. Table 2.SM.12 provides an overview of geophysical characteristics per class.

Table 2.SM.11: Overview of pathway class specifications

Pathway group	**Class name**	**Short name combined classes**	**MAGICC exceedance probability filter**	**Number of scenarios**
1.5°C	Below 1.5°C	-	**$P(1.5^\circ C) \leq 0.34$**	**0**
	Below 1.5°C	Below-1.5°C	**$0.34 < P(1.5^\circ C) \leq 0.5$**	**9**
	1.5°C Return with low OS	1.5°C-low-OS	**$0.5 < P(1.5^\circ C) \leq 0.67$** AND **$P(1.5^\circ C \text{ in } 2100) \leq 0.5$**	**34**
			$0.5 < P(1.5^\circ C) \leq 0.67$ AND **$0.34 < P(1.5^\circ C \text{ in } 2100) \leq 0.5$**	**10**
	1.5°C Return with high OS	1.5°C-high-OS	**$0.67 < P(1.5^\circ C)$** AND **$P(1.5^\circ C \text{ in } 2100) \leq 0.34$**	**19**
			$0.67 < P(1.5^\circ C)$ AND **$0.34 < P(1.5^\circ C \text{ in } 2100) \leq 0.5$**	**18**
2°C	Lower 2°C	Lower-2°C	**$P(2^\circ C) \leq 0.34$** (excluding above)	**74**
	Higher 2°C	Higher-2°C	**$0.34 < P(2^\circ C) \leq 0.5$** (excluding above)	**58**
	Above 2°C	-	**$0.5 < P(2^\circ C)$**	**189**

As noted in the chapter text, scenario classification was based on probabilistic temperature outcomes assessed using the AR5 assessment of composition, forcing and climate response. These were represented within the MAGICC model (Meinshausen et al., 2009, 2011a) which was used in the same setup as AR5 WGIII analyses. As discussed in Section 2.2, updates in geophysical understanding would alter such results were they incorporated within MAGICC, though central outcomes would remain well within the probability distribution of the setup used here (see Section 2.SM.1.1).

Table 2.SM.12: Geophysical characteristics of mitigation pathways derived at median peak temperature and at the end of the century (2100). Geophysical characteristics of overshoot for mitigation pathways exceeding 1.5°C is given in the last two columns. Overshoot severity is the sum of degree warming years exceeding 1.5°C over the 21st century. NA indicates that no mitigation pathways exhibits the given geophysical characteristics. Radiative forcing metrics are: total anthropogenic radiative forcing (RFall), CO_2 radiative forcing (RFCO_2), and non-CO_2 radiative forcing (RFnonCO_2). Cumulative CO2 emissions until peak warming or 2100 are given for submitted (Subm.) and harmonized (Harm.) IAM outputs and are rounded at the nearest 10 GtCO_2.

			Geophysical characteristics at peak warming											Geophysical characteristics in 2100									Geophysical characteristics of the temperature overshoot				
category	# scenario with climate assessment	peak|median warming	peak|year	peak|CO_2 [ppm]	peak|RF all [Wm2]	peak|RF CO_2 [Wm2]	peak|RF non CO_2 [Wm2]	netzero CO_2 |year	cumulative CO_2 emissions (2016 to peak, as submitted)	cumulative CO_2 emissions (2016 to peak, harmonized)	peak|Prob Exceed 1.5°C [%]	peak|Prob Exceed 2.0°C [%	peak|Prob Exceed 2.5°C [%	2100| CO_2 [ppm]	2100|RF all [Wm2]	2100|RF CO_2 [Wm2]	2100|RF non CO_2 [Wm2]	cumulative CO_2 emissions (2016-2100), as submitted	cumulative CO_2 emissions (2016-2100), harmonized	2100|Prob Exceed 1.5°C [%	2100|Prob Exceed 2.0°C [%	2100|Prob Exceed 2.5°C [%	Overshoot|Duration [years]|2.0°C	Overshoot|Exceedance year|1.5°C	Overshoot|Exceedance year|2.0°C	Overshoot|Severity [temperature-years]|1.5°C	Overshoot|Duration [years]|1.5°C

2.SM.1.5 Mitigation and SDG pathway synthesis

The Chapter 2 synthesis assessment (see Figure 2.28) of interactions between 1.5°C mitigation pathways and sustainable development or Sustainable Development Goals (SDGs) is based on the assessment of interactions of mitigation measures and SDGs carried out by Chapter 5 (Section 5.4). To derive a synthesis assessment of the interactions between 1.5°C mitigation pathways and SDGs, a set of clear and transparent steps are followed, as described below.

- Table 5.1 is at the basis of all interactions considered between mitigation measures and SDGs.
- A condensed set of mitigation measures, selecting and combining mitigation measures from Table 5.1, is defined (see Table 2.SM.13).
- If a measure in the condensed Chapter 2 set is a combination of multiple mitigation measures from Table 5.1, the main interaction (synergies, synergy or trade-off, trade-off) is based on all interactions with 3* and 4* confidence in Table 5.1. If no 3* or 4* interactions are available, lower confidence interactions are considered if available.
- The resulting interaction is defined by the interaction of the majority of cells.
- If one cell shows a diverging interaction and this interaction has 3* or more confidence level, a “synergy or trade-off” interaction is considered.
- If all interactions for a given mitigation measure and SDG combination are the same, the resulting interaction is represented with a bold symbol.
- If all 3* and 4* interactions are of the same nature, but a lower confidence interaction is opposite, the interaction is represented with a regular symbol.
- Confidence is defined by the rounded average of all available confidence levels of the predominant direction (rounded down; 4* confidence in Table 5.1 is also reported as 3* in the Chapter 2 synthesis)
- If a measure in Table 5.1 is assessed to result in either a neutral effect or a synergy or trade-off, the synergy or trade-off is reported in the Chapter 2 synthesis, but the confidence level is reduced by one notch.

To derive relative synergy-risk profiles for the four scenario archetypes used in Chapter 2 (S1, S2, S5, LED, see Sections 2.1 and 2.3), the relative deployment of the selected mitigation measures is used. For each mitigation measure, a proxy indicator is used (see Table 2.SM.14). The proxy indicator values are displayed on a relative scale from zero to one where the value of the lowest pathway is set to the origin and the values of the other pathways scaled so that the maximum is one. The pathways with proxy indicators values that are neither 0 nor 1, receive a 0.5 weighting. These 0, 0.5, or 1 values are used to determine the relative achievement of specific synergies or trade-offs per SDG in each scenario, by summation of each respective interaction type (synergy, trade-off, or synergy or trade-off) over all proxy indicators. Ultimately these sums are synthesized in one interaction based on the majority of sub-interactions (synergy, trade-off, or synergy or trade-off). In cases where both synergies and trade-offs are identified, the ‘synergy or trade-off’ interaction is attributed.

Table 2.SM.13: Mapping of mitigation measures assessed in Table 5.1 of Chapter 5 to the condensed set of mitigation measured used for the mitigation-SDG synthesis of Chapter 2.

			🟦
			🟦
			🟧
			🟦
			🟦
			🟦
			🟦
			🟦
			🟦
			🟦
			🟦
			🟦
			🟦
			🟦
			🟦
			🟦
			🟦
			🟦
			🟦
			🟧
			🟧
			🟧
			🟧

Table 2.SM.14: Mitigation measure and proxy indicators reflecting relative deployment of given measure across pathway archetypes. Values of Indicators 2, 3, and 4 are inverse related with the deployment of the respective measures.

Mitigation measure		**Pathway proxy**	
Group	*description*	*number*	*description*
Demand			
Supply			
Land			

References

Ackerman, F., S.J. DeCanio, R.B. Howarth, and K. Sheeran, 2009: Limitations of integrated assessment models of climate change. *Climatic Change***, 95(3-4)**, 297-315, doi:10.1007/s10584-009-9570-x.

Adler, M.D. et al., 2017: Priority for the worse-off and the social cost of carbon. *Nature Clim. Change***, 7(6)**, 443-449, doi:10.1038/nclimate3298.

Allen, M.R. et al., 2018: Quantifying the impact of climate change agreements covering cumulative and short-lived climate pollutants. *Nature* (in press).

Amann, M., Z. Klimont, and F. Wagner, 2013: Regional and Global Emissions of Air Pollutants: Recent Trends and Future Scenarios. *Annual Review of Environment and Resources***, 38(1)**, 31-55, doi:10.1146/annurev-environ-052912-173303.

Bauer, N. et al., 2017: Shared Socio-Economic Pathways of the Energy Sector - Quantifying the Narratives. *Global Environmental Change***, 42**, 316-330, doi:10.1016/j.gloenvcha.2016.07.006.

Bauer, N. et al., 2018: Global energy sector emission reductions and bioenergy use: overview of the bioenergy demand phase of the EMF 33 model comparison. *Climatic Change* (in press), doi:10.1007/s10584-018-2226-y.

Beck, S. and M. Mahony, 2017: The IPCC and the politics of anticipation. *Nature Climate Change***, 7(5)**, 311-313, doi:10.1038/nclimate3264.

Bertram, C., G. Luderer, A. Popp, J.C. Minx, and W. Lamb, 2018: Targeted policies can compensate most of the increased sustainability risks in 1.5°C mitigation scenarios. *Environ. Res. Lett* (in press).

Bertram, C. et al., 2015: Complementing carbon prices with technology policies to keep climate targets within reach. *Nature Climate Change***, 5(3)**, 235-239, doi:10.1038/nclimate2514.

Blanford, G.J., E. Kriegler, and M. Tavoni, 2014: Harmonization vs. fragmentation: Overview of climate policy scenarios in EMF27. *Climatic Change***, 123(3-4)**, 383-396, doi:10.1007/s10584-013-0951-9.

Bonsch, M. et al., 2014: Trade-offs between land and water requirements for large-scale bioenergy production. *GCB Bioenergy***, 8(1)**, 11-24, doi:10.1111/gcbb.12226.

Brunner, S. and K. Enting, 2014: Climate finance: A transaction cost perspective on the structure of state-to-state transfers. *Global Environmental Change***, 27**, 138-143.

Burke, M., S.M. Hsiang, and E. Miguel, 2015: Global non-linear effect of temperature on economic production. *Nature***, 527**, 235-239, doi:10.1038/nature15725.

Burke, M., W.M. Davis, and N.S. Diffenbaugh, 2018: Large potential reduction in economic damages under UN mitigation targets. *Nature***, 557(7706)**, 549-553, doi:10.1038/s41586-018-0071-9.

Burke, M. et al., 2016: Opportunities for advances in climate change economics. *Science***, 352(6283)**, 292-293, doi:10.1126/science.aad9634.

Cai, Y., K.L. Judd, T.M. Lenton, T.S. Lontzek, and D. Narita, 2015: Environmental tipping points significantly affect the cost-benefit assessment of climate policies. *Proceedings of the National Academy of Sciences***, 112(15)**, 4606-4611, doi:10.1073/pnas.1503890112.

Cameron, C. et al., 2016: Policy trade-offs between climate mitigation and clean cook-stove access in South Asia. *Nature Energy***, 1(1)**, 15010, doi:10.1038/nenergy.2015.10.

Chen, C. and M. Tavoni, 2013: Direct air capture of CO2 and climate stabilization: A model based assessment. *Climatic Change***, 118(1)**, 59-72, doi:10.1007/s10584-013-0714-7.

Chilvers, J. et al., 2017: Realising transition pathways for a more electric, low-carbon energy system in the United Kingdom: Challenges, insights and opportunities. *Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy***, 231(6)**, 440-477, doi:10.1177/0957650917695448.

Clarke, L. et al., 2009: International climate policy architectures: Overview of the EMF 22 International Scenarios. *Energy Economics***, 31**, S64-S81, doi:10.1016/j.eneco.2009.10.013.

Clarke, L. et al., 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, pp. 413-510.

Collins, M. et al., 2013: Long-term Climate Change: Projections, Commitments and Irreversibility. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.–K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1029-1136.

Craxton, M., J. Merrick, C. Makridis, and J. Taggart, 2017: On the climate policy implications of substitutability and flexibility in the economy: An in-depth integrated assessment model diagnostic. *Technological Forecasting and Social Change***, 125**, 289-298, doi:https://doi.org/10.1016/j.techfore.2017.07.003.

Creutzig, F. et al., 2017: The underestimated potential of solar energy to mitigate climate change. *Nature Energy***, 2(9)**, 17140, doi:10.1038/nenergy.2017.140.

Dell, M., B.F. Jones, and B.A. Olken, 2014: What Do We Learn from the Weather ? The New Climate-Economy

Literature. *Journal of Economic Literature*, **52(3)**, 740-798.

Dennig, F., M.B. Budolfson, M. Fleurbaey, A. Siebert, and R.H. Socolow, 2015: Inequality, climate impacts on the future poor, and carbon prices. *Proceedings of the National Academy of Sciences*, **112(52)**, 15827-15832, doi:10.1073/pnas.1513967112.

Dietz, S. and N. Stern, 2008: Why Economic Analysis Supports Strong Action on Climate Change: A Response to the Stern Review's Critics. *Review of Environmental Economics and Policy*, **2(1)**, 94-113, doi:10.1093/reep/ren001.

Edelenbosch, O.Y. et al., 2017a: Comparing projections of industrial energy demand and greenhouse gas emissions in long-term energy models. *Energy*, **122**, 701-710, doi:10.1016/J.ENERGY.2017.01.017.

Edelenbosch, O.Y. et al., 2017b: Decomposing passenger transport futures: Comparing results of global integrated assessment models. *Transportation Research Part D: Transport and Environment*, **55**, 281-293, doi:10.1016/j.trd.2016.07.003.

Edelenbosch, O.Y. et al., 2017c: Transport fuel demand responses to fuel price and income projections: Comparison of integrated assessment models. *Transportation Research Part D: Transport and Environment*, **55**, 310-321, doi:10.1016/J.TRD.2017.03.005.

Edenhofer, O. and M. Kowarsch, 2015: Cartography of pathways: A new model for environmental policy assessments. *Environmental Science & Policy*, **51**, 56-64, doi:10.1016/j.envsci.2015.03.017.

Edenhofer, O. et al., 2010: The Economics of Low Stabilization: Model Comparison of Mitigation Strategies and Costs. *The Energy Journal*, **31(Special Issue 1)**, 11-48, doi:10.2307/41323490.

Etminan, M., G. Myhre, E.J. Highwood, and K.P. Shine, 2016: Radiative forcing of carbon dioxide, methane, and nitrous oxide: A significant revision of the methane radiative forcing. *Geophysical Research Letters*, **43(24)**, 12,614-12,623, doi:10.1002/2016GL071930.

Figueres, C. et al., 2017: Three years to safeguard our climate. *Nature*, **546(7660)**, 593-595, doi:10.1038/546593a.

Forster, P. et al., 2007: Changes in Atmospheric Constituents and in Radiative Forcing. *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, 129-234.

Frank, S. et al., 2017: Reducing greenhouse gas emissions in agriculture without compromising food security? *Environmental Research Letters*, **12(10)**, 105004, doi:10.1088/1748-9326/aa8c83.

Frank, S. et al., 2018: Structural change as a key component for agricultural non-CO2 mitigation efforts. *Nature Communications*, **9(1)**, 1060, doi:10.1038/s41467-018-03489-1.

Fricko, O. et al., 2016: Energy sector water use implications of a 2 °C climate policy. *Environmental Research Letters*, **11(3)**, 034011, doi:10.1088/1748-9326/11/3/034011.

Geels, F.W., B.K. Sovacool, T. Schwanen, and S. Sorrell, 2017: Sociotechnical transitions for deep decarbonization. *Science*, **357(6357)**.

Grubb, M., J.C. Hourcade, and K. Neuhoff, 2014: *Planetary economics: energy, climate change and the three domains of sustainable development*. Routledge Earthscan, Oxon, New York, 520 pp.

Grubler, A., 2010: The costs of the French nuclear scale-up: A case of negative learning by doing. *Energy Policy*, **38(9)**, 5174-5188, doi:10.1016/J.ENPOL.2010.05.003.

Grubler, A. et al., 2018: A Global Scenario of Low Energy Demand for Sustainable Development below 1.5°C without Negative Emission Technologies. *Nature Energy* (in press), doi:10.1038/s41560-018-0172-6.

Gschrey, B., W. Schwarz, C. Elsner, and R. Engelhardt, 2011: High increase of global F-gas emissions until 2050. *Greenhouse Gas Measurement and Management*, **1(2)**, 85-92, doi:10.1080/20430779.2011.579352.

Guivarch, C., R. Crassous, O. Sassi, and S. Hallegatte, 2011: The costs of climate policies in a second-best world with labour market imperfections. *Climate Policy*, **11(1)**, 768-788, doi:10.3763/cpol.2009.0012.

Haegel, N.M. et al., 2017: Terawatt-scale photovoltaics: Trajectories and challenges. *Science*, **356(6334)**, 141-143, doi:10.1126/science.aal1288.

Hallegatte, S. and J. Rozenberg, 2017: Climate change through a poverty lens. *Nature Climate Change*, **7**, 250.

Havlík, P. et al., 2014: Climate change mitigation through livestock system transitions. *Proceedings of the National Academy of Sciences of the United States of America*, **111(10)**, 3709-14, doi:10.1073/pnas.1308044111.

Hejazi, M. et al., 2014: Long-term global water projections using six socioeconomic scenarios in an integrated assessment modeling framework. *Technological Forecasting and Social Change*, **81**, 205-226, doi:10.1016/j.techfore.2013.05.006.

Hoesly, R.M. et al., 2018: Historical (1750-2014) anthropogenic emissions of reactive gases and aerosols from the Community Emissions Data System (CEDS). *Geoscientific Model Development*, **11(1)**, 369-408, doi:10.5194/gmd-11-369-2018.

Holz, C., L. Siegel, E. Johnston, A.P. Jones, and J. Sterman, 2018: Ratcheting ambition to limit warming to 1.5°C - trade-offs between emission reductions and carbon dioxide removal. *Environmental Research Letters* (in press), doi:10.1088/1748-9326/aac0c1.

Houghton, R. et al., 2012: Carbon emissions from land use and land-cover change. *Biogeosciences*, **9(12)**, 5125-5142, doi:10.5194/bg-9-5125-2012.

Hsiang, S. et al., 2017: Estimating economic damage from climate change in the United States. *Science*, **356(6345)**, 1362 LP - 1369.

Humpenöder, F. et al., 2018: Large-scale bioenergy production: how to resolve sustainability trade-offs? *Environmental*

*Research Letters***, 13(2)**, 024011, doi:10.1088/1748-9326/aa9e3b.

IEA, 2017: *Energy Technology Perspectives 2017*. International Energy Agency (IEA), Paris, France, 443 pp.

Iyer, G.C. et al., 2015: Improved representation of investment decisions in assessments of CO2 mitigation. *Nature Climate Change***, 5(5)**, 436-440, doi:10.1038/nclimate2553.

Johnson, N. et al., 2017: A reduced-form approach for representing the impacts of wind and solar PV deployment on the structure and operation of the electricity system. *Energy Economics***, 64**, 651-664, doi:10.1016/J.ENECO.2016.07.010.

Knutti, R. and J. Rogelj, 2015: The legacy of our CO2 emissions: a clash of scientific facts, politics and ethics. *Climatic Change***, 133(3)**, 361-373, doi:10.1007/s10584-015-1340-3.

Kolstad, C. et al., 2014: Social, Economic and Ethical Concepts and Methods. 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. Kadne, 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 Univeristy Press, Cambridge, United Kingdom and New York, NY, USA, pp. 207-282.

Krey, V., G. Luderer, L. Clarke, and E. Kriegler, 2014a: Getting from here to there - energy technology transformation pathways in the EMF27 scenarios. *Climatic Change***, 123**, 369-382, doi:10.1007/s10584-013-0947-5.

Krey, V. et al., 2014b: Annex II: Metrics & Methodology. 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, pp. 1281-1328.

Kriegler, E. et al., 2014: 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(3-4)**, 353-367, doi:10.1007/s10584-013-0953-7.

Kriegler, E. et al., 2015a: Diagnostic indicators for integrated assessment models of climate policy. *Technological Forecasting and Social Change***, 90(PA)**, 45-61, doi:10.1016/j.techfore.2013.09.020.

Kriegler, E. et al., 2015b: Making or breaking climate targets: The AMPERE study on staged accession scenarios for climate policy. *Technological Forecasting and Social Change***, 90(PA)**, 24-44, doi:10.1016/j.techfore.2013.09.021.

Kriegler, E. et al., 2016: Will economic growth and fossil fuel scarcity help or hinder climate stabilization?: Overview of the RoSE multi-model study. *Climatic Change***, 136(1)**, 7-22, doi:10.1007/s10584-016-1668-3.

Kriegler, E. et al., 2018: Short term policies to keep the door open for Paris climate goals. *Environ. Res. Lett* (in press), doi:10.1088/1748-9326/aac4f1.

Kunreuther, H. et al., 2014: Integrated Risk and Uncertainty Assessment of Climate Change Response Policies. 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.

Laitner, J., S. De Canio, and I. Peters, 2000: Incorporating Behavioural, Social, and Organizational Phenomena in the Assessment of Climate Change Mitigation Options. *Society, Behaviour, and Climate Change Mitigation*, 1-64, doi:10.1007/0-306-48160-X_1.

Le Quéré, C. et al., 2016: Global Carbon Budget 2016. *Earth System Science Data***, 8(2)**, 605-649, doi:10.5194/essd-8-605-2016.

Le Quéré, C. et al., 2018: Global Carbon Budget 2017. *Earth Syst. Sci. Data***, 1010333739(10)**, 405-448, doi:10.5194/essd-10-405-2018.

Leach, N.J. et al., 2018: Current level and rate of warming determine emissions budgets under ambitious mitigation. *Nature Geoscience* (in press).

Li, F.G.N. and N. Strachan, 2017: Modelling energy transitions for climate targets under landscape and actor inertia. *Environmental Innovation and Societal Transitions***, 24**, 106-129, doi:10.1016/j.eist.2016.08.002.

Li, F.G.N., E. Trutnevyte, and N. Strachan, 2015: A review of socio-technical energy transition (STET) models. *Technological Forecasting and Social Change***, 100**, 290-305, doi:10.1016/j.techfore.2015.07.017.

Liu, J.–Y. et al., 2017: Socio-economic factors and future challenges of the goal of limiting the increase in global average temperature to 1.5°C. *Carbon Management* (in press).

Löffler, K. et al., 2017: Designing a Model for the Global Energy System-GENeSYS-MOD: An Application of the Open-Source Energy Modeling System (OSeMOSYS). *Energies***, 10(10)**, 1468, doi:10.3390/en10101468.

Lontzek, T.S., Y. Cai, K.L. Judd, and T.M. Lenton, 2015: Stochastic integrated assessment of climate tipping points indicates the need for strict climate policy. *Nature Climate Change***, 5(5)**, 441-444.

Lucon, O. et al., 2014: Buildings. 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, pp. 671-738.

Luderer, G., C. Bertram, K. Calvin, E. De Cian, and E. Kriegler, 2016: Implications of weak near-term climate policies on long-term mitigation pathways. *Climatic Change***, 136(1)**, 127-140, doi:10.1007/s10584-013-0899-9.

Luderer, G. et al., 2012: The economics of decarbonizing the energy system - results and insights from the RECIPE model intercomparison. *Climatic Change***, 114(1)**, 9-37, doi:10.1007/s10584-011-0105-x.

Luderer, G. et al., 2013: Economic mitigation challenges: how further delay closes the door for achieving climate targets. *Environmental Research Letters***, 8(3)**, 034033, doi:10.1088/1748-9326/8/3/034033.

Luderer, G. et al., 2017: Assessment of wind and solar power in global low-carbon energy scenarios: An introduction. *Energy Economics***, 64**, 542-551, doi:10.1016/J.ENECO.2017.03.027.

Luderer, G. et al., 2018: Residual fossil CO2 emissions in 1.5-2°C pathways. *Nature Climate Change* (in press), doi:10.1038/s41558-018-0198-6.

Marcucci, A., S. Kypreos, and E. Panos, 2017: The road to achieving the long-term Paris targets: Energy transition and the role of direct air capture. *Climatic Change***, 144(2)**, 181-193, doi:10.1007/s10584-017-2051-8.

McCollum, D.L., W. Zhou, C. Bertram, H.–S. de Boer, and V. Bosetti, 2018: Energy investment needs for fulfilling the Paris Agreement and achieving the Sustainable Development Goals. *Nature Energy* (in press), doi:10.1038/s41560-018-0179-z.

McCollum, D.L. et al., 2016: Improving the behavioral realism of global integrated assessment models: An application to consumers' vehicle choices. *Transportation Research Part D: Transport and Environment*, doi:10.1016/j.trd.2016.04.003.

Meinshausen, M., T.M.L. Wigley, and S.C.B. Raper, 2011a: Emulating atmosphere-ocean and carbon cycle models with a simpler model, MAGICC6 - Part 2: Applications. *Atmospheric Chemistry and Physics***, 11(4)**, 1457-1471, doi:10.5194/acp-11-1457-2011.

Meinshausen, M. et al., 2009: Greenhouse-gas emission targets for limiting global warming to 2 °C. *Nature***, 458(7242)**, 1158-1162, doi:10.1038/nature08017.

Meinshausen, M. et al., 2011b: The RCP greenhouse gas concentrations and their extensions from 1765 to 2300. *Climatic Change***, 109(1-2)**, 213-241, doi:10.1007/s10584-011-0156-z.

Mercure, J.–F. et al., 2018: Environmental impact assessment for climate change policy with the simulation-based integrated assessment model E3ME-FTT-GENIE. *Energy Strategy Reviews***, 20**, 195-208, doi:https://doi.org/10.1016/j.esr.2018.03.003.

Mouratiadou, I., A. Biewald, and M. Pehl, 2016: The impact of climate change mitigation on water demand for energy and food: An integrated analysis based on the Shared Socioeconomic Pathways. *Environmental Science & Policy***, 64**, 48-58.

Mouratiadou, I. et al., 2018: Water demand for electricity in deep decarbonisation scenarios: a multi-model assessment. *Climatic Change***, 147(1)**, 91-106, doi:10.1007/s10584-017-2117-7.

Mundaca, L., L. Neij, E. Worrell, and M. McNeil, 2010: Evaluating Energy Efficiency Policies with Energy-Economy Models. *Annual Review of Environment and Resources***, 35(1)**, 305-344, doi:10.1146/annurev-environ-052810-164840.

Mundaca, L., M. Mansoz, L. Neij, and G. Timilsina, 2013: Transaction costs analysis of low-carbon technologies. *Climate Policy***, 13(4)**, 490-513, doi:10.1080/14693062.2013.781452.

Myhre, G. et al., 2013: Anthropogenic and Natural Radiative Forcing. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.–K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 659-740.

Myhre, G. et al., 2017: Multi-model simulations of aerosol and ozone radiative forcing due to anthropogenic emission changes during the period 1990-2015. *Atmospheric Chemistry and Physics***, 17(4)**, doi:10.5194/acp-17-2709-2017.

Nordhaus, W.D., 2005: A Review of The Stern Review on the Economics of Climate Change. *Journal of Economic Literature***, XLV**, 686-702.

OECD/IEA and IRENA, 2017: *Perspectives for the Energy Transition: Investment Needs for a Low-Carbon Energy System*. OECD/IEA and IRENA, 204 pp.

Parkinson, S.C., V. Krey, and D. Huppmann, 2017: Quantifying interactions between SDG6 and a 1.5°C climate policy. (in press).

Patt, A.G., 2015: *Transforming energy: Solving climate change with technology policy*. Cambridge University Press, New york, 349 pp.

Patt, A.G. et al., 2010: Adaptation in integrated assessment modeling: where do we stand? *Climatic Change***, 99**, 383-402, doi:10.1007/s10584-009-9687-y.

Pauliuk, S., A. Arvesen, K. Stadler, and E.G. Hertwich, 2017: Industrial ecology in integrated assessment models. *Nature Climate Change***, 7(1)**, 13-20, doi:10.1038/nclimate3148.

Pietzcker, R.C. et al., 2017: System integration of wind and solar power in integrated assessment models: A cross-model evaluation of new approaches. *Energy Economics***, 64**, 583-599, doi:10.1016/j.eneco.2016.11.018.

Pizer, W. et al., 2014: Using and improving the social cost of carbon. *Science***, 346(6214)**, 1189-1190, doi:10.1126/science.1259774.

Popp, A. et al., 2014: Land-use transition for bioenergy and climate stabilization: Model comparison of drivers, impacts and interactions with other land use based mitigation options. *Climatic Change***, 123(3-4)**, 495-509, doi:10.1007/s10584-013-0926-x.

Popp, A. et al., 2017: Land-use futures in the shared socio-economic pathways. *Global Environmental Change***, 42**, 331-345, doi:10.1016/j.gloenvcha.2016.10.002.

Rao, S. et al., 2017: Future air pollution in the Shared Socio-economic Pathways. *Global Environmental Change***, 42**, 346-358, doi:10.1016/j.gloenvcha.2016.05.012.

Revesz, R. et al., 2014: Global warming: Improve economic models of climate change. *Nature***, 508(7495)**, 173-175, doi:10.1038/508173a.

Riahi, K. et al., 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(PA)**, 8-23, doi:10.1016/j.techfore.2013.09.016.

Riahi, K. et al., 2017: The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. *Global Environmental Change***, 42**, 153-168, doi:10.1016/j.gloenvcha.2016.05.009.

Rockström, J. et al., 2017: A roadmap for rapid decarbonization. *Science***, 355(6331)**, 1269-1271, doi:10.1126/science.aah3443.

Rogelj, J., D.L. McCollum, B.C. O'Neill, and K. Riahi, 2013a: 2020 emissions levels required to limit warming to below 2 C. *Nature Climate Change***, 3(4)**, 405-412, doi:10.1038/nclimate1758.

Rogelj, J., D.L. McCollum, A. Reisinger, M. Meinshausen, and K. Riahi, 2013b: Probabilistic cost estimates for climate change mitigation. *Nature***, 493(7430)**, 79-83, doi:10.1038/nature11787.

Rogelj, J. et al., 2014: Disentangling the effects of CO2 and short-lived climate forcer mitigation. *Proceedings of the National Academy of Sciences***, 111(46)**, 16325-16330, doi:10.1073/pnas.1415631111.

Rogelj, J. et al., 2015: Energy system transformations for limiting end-of-century warming to below 1.5 °C. *Nature Climate Change***, 5(6)**, 519-527, doi:10.1038/nclimate2572.

Rogelj, J. et al., 2018: Scenarios towards limiting global mean temperature increase below 1.5 °C. *Nature Climate Change***, 8(4)**, 325-332, doi:10.1038/s41558-018-0091-3.

Rubin, E.S., J.E. Davison, and H.J. Herzog, 2015: The cost of CO2 capture and storage. *International Journal of Greenhouse Gas Control***, 40**, 378-400, doi:10.1016/J.IJGGC.2015.05.018.

Schneider von Deimling, T. et al., 2012: Estimating the near-surface permafrost-carbon feedback on global warming. *Biogeosciences***, 9(2)**, 649-665, doi:10.5194/bg-9-649-2012.

Schneider von Deimling, T. et al., 2015: Observation-based modelling of permafrost carbon fluxes with accounting for deep carbon deposits and thermokarst activity. *Biogeosciences***, 12(11)**, 3469-3488, doi:10.5194/bg-12-3469-2015.

Schwanitz, V.J., 2013: Evaluating integrated assessment models of global climate change. *Environmental Modelling & Software***, 50**, 120-131, doi:10.1016/j.envsoft.2013.09.005.

Shah, N., M. Wei, V. Letschert, and A. Phadke, 2015: *Benefits of Leapfrogging to Superefficiency and Low Global Warming Potential Refrigerants in Room Air Conditioning*. LBNL-1003671, 58 pp.

Shell International B.V., 2018: *Shell Scenarios: Sky - Meeting the Goals of the Paris Agreement*. Shell International B.V. 36 pp.

Shindell, D.T. et al., 2012: Simultaneously Mitigating Near-Term Climate Change and Improving Human Health and Food Security. *Science***, 335(6065)**, 183-189, doi:10.1126/science.1210026.

Smith, C.J. et al., 2018: FAIR v1.3: A simple emissions-based impulse response and carbon cycle model. *Geoscientific Model Development* (in press), doi:10.5194/gmd-2017-266.

Stanton, E.A., F. Ackerman, and S. Kartha, 2009: Inside the integrated assessment models: Four issues in climate economics. *Climate and Development***, 1(2)**, 166, doi:10.3763/cdev.2009.0015.

Stern, N., 2016: Current climate models are grossly misleading. *Nature***, 530**, 407-409, doi:10.1038/530407a.

Stevanović, M. et al., 2016: The impact of high-end climate change on agricultural welfare. *Science Advances***, 2(8)**, e1501452, doi:10.1126/sciadv.1501452.

Stiglitz, J.E. et al., 2017: *Report of the High-Level Commission on Carbon Prices*. Carbon Pricing Leadership Coalition, 68 pp.

Stocker, T.F. et al., 2013: Technical Summary. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.–K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 33-115.

Strefler, J., T. Amann, N. Bauer, E. Kriegler, and J. Hartmann, 2018a: Potential and costs of carbon dioxide removal by enhanced weathering of rocks. *Environmental Research Letters***, 13(3)**, 034010, doi:10.1088/1748-9326/aaa9c4.

Strefler, J., N. Bauer, E. Kriegler, A. Popp, and O. Giannousakis, Anastasis Edenhofer, 2018b: Between Scylla and Charybdis: Delayed mitigation narrows the passage between large-scale CDR and high costs. *Environ. Res. Lett***, 13**, 044015.

Sussams, L. and J. Leaton, 2017: *Expect the Unexpected - The Disruptive Power of Low-carbon Technology*. 52 pp.

Tavoni, M., E. De Cian, G. Luderer, J.C. Steckel, and H. Waisman, 2012: The value of technology and of its evolution towards a low carbon economy. *Climatic Change*, **114(1)**, 39-57, doi:10.1007/s10584-011-0294-3.

Tavoni, M. et al., 2015: Post-2020 climate agreements in the major economies assessed in the light of global models. *Nature Climate Change*, **5(2)**, 119-126, doi:10.1038/nclimate2475.

Trutnevyte, E., N. Strachan, P.E. Dodds, D. Pudjianto, and G. Strbac, 2015: Synergies and trade-offs between governance and costs in electricity system transition. *Energy Policy*, **85**, 170-181, doi:10.1016/j.enpol.2015.06.003.

Turnheim, B. et al., 2015: Evaluating sustainability transitions pathways: Bridging analytical approaches to address governance challenges. *Global Environmental Change*, **35**, 239-253, doi:10.1016/j.gloenvcha.2015.08.010.

Ürge-Vorsatz, D., A. Novikova, S. Köppel, and B. Boza-Kiss, 2009: Bottom-up assessment of potentials and costs of CO2 emission mitigation in the buildings sector: insights into the missing elements. *Energy Efficiency*, **2(4)**, 293-316, doi:10.1007/s12053-009-9051-0.

van Marle, M.J.E. et al., 2017: Historic global biomass burning emissions for CMIP6 (BB4CMIP) based on merging satellite observations with proxies and fire models (1750-2015). *Geoscientific Model Development*, **10(9)**, 3329-3357, doi:10.5194/gmd-10-3329-2017.

van Sluisveld, M.A.E., S.H. Martínez, V. Daioglou, and D.P. van Vuuren, 2016: 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, doi:10.1016/J.TECHFORE.2015.08.013.

van Sluisveld, M.A.E. et al., 2015: Comparing future patterns of energy system change in 2 °C scenarios with historically observed rates of change. *Global Environmental Change*, **35**, 436-449, doi:10.1016/j.gloenvcha.2015.09.019.

van Vuuren, D.P. et al., 2011: The representative concentration pathways: An overview. *Climatic Change*, **109(1)**, 5-31, doi:10.1007/s10584-011-0148-z.

van Vuuren, D.P. et al., 2015: Pathways to achieve a set of ambitious global sustainability objectives by 2050: Explorations using the IMAGE integrated assessment model. *Technological Forecasting and Social Change*, **98**, 303-323, doi:10.1016/J.TECHFORE.2015.03.005.

van Vuuren, D.P. et al., 2018: Alternative pathways to the 1.5 °C target reduce the need for negative emission technologies. *Nature Climate Change*, **8(5)**, 391-397, doi:10.1038/s41558-018-0119-8.

Velders, G.J.M., D.W. Fahey, J.S. Daniel, S.O. Andersen, and M. McFarland, 2015: Future atmospheric abundances and climate forcings from scenarios of global and regional hydrofluorocarbon (HFC) emissions. *Atmospheric Environment*, **123**, 200-209, doi:10.1016/j.atmosenv.2015.10.071.

Vrontisi, Z. et al., 2018: A multi-model assessment of the short-term effectiveness of Paris pledges towards a 1.5-2°C stabilization. *Environ. Res. Lett*, **13**, 044039, doi:10.1088/1748-9326/aab53e.

Warszawski, L. et al., 2014: The Inter-Sectoral Impact Model Intercomparison Project (ISIMIP): Project framework. *Proceedings of the National Academy of Sciences*, **111(9)**, 3228-3232, doi:10.1073/pnas.1312330110.

Weindl, I. et al., 2017: Livestock and human use of land: Productivity trends and dietary choices as drivers of future land and carbon dynamics. *Global and Planetary Change*, **159**, 1-10, doi:10.1016/j.gloplacha.2017.10.002.

Weyant, J., 2017: Some Contributions of Integrated Assessment Models of Global Climate Change. *Review of Environmental Economics and Policy*, **11(1)**, 115-137, doi:10.1093/reep/rew018.

Wilkerson, J.T., B.D. Leibowicz, D.D. Turner, and J.P. Weyant, 2015: Comparison of integrated assessment models: Carbon price impacts on U.S. energy. *Energy Policy*, **76**, 18-31, doi:https://doi.org/10.1016/j.enpol.2014.10.011.

Wilson, C. and H. Dowlatabadi, 2007: Models of Decision Making and Residential Energy Use. *Annual Review of Environment and Resources*, **32(1)**, 169-203, doi:10.1146/annurev.energy.32.053006.141137.

Wilson, C., A. Grubler, K.S. Gallagher, and G.F. Nemet, 2012: Marginalization of end-use technologies in energy innovation for climate protection. *Nature Climate Change*, **2(11)**, 780-788, doi:10.1038/NCLIMATE1576.

Wilson, C., A. Grubler, N. Bauer, V. Krey, and K. Riahi, 2013: Future capacity growth of energy technologies: are scenarios consistent with historical evidence? *Climatic Change*, **118(2)**, 381-395, doi:10.1007/s10584-012-0618-y.

Wilson, C. et al., 2017: Evaluating Process-Based Integrated Assessment Models of Climate Change Mitigation. IIASA Working Paper WP-17-007.

Wong-Parodi, G., T. Krishnamurti, A. Davis, D. Schwartz, and B. Fischhoff, 2016: A decision science approach for integrating social science in climate and energy solutions. *Nature Climate Change*, **6(6)**, 563-569, doi:10.1038/nclimate2917.

Zhang, R., S. Fujimori, and T. Hanaoka, 2018: The contribution of transport policies to the mitigation potential and cost of 2°C and 1.5°C goals. *Environmental Research Letters*, **13(5)**, 054008.

2.SM.2 Part 2

Contributing modelling framework reference cards
For each of the contributing modelling frameworks a reference card has been created highlighting the key features of the model. These reference cards are either based on information received from contributing modelling teams upon submission of scenarios to the SR1.5 database, or alternatively drawn from the ADVANCE IAM wiki documentation, available at http://www.fp7-advance.eu/content/model-documentation, and updated. These reference cards are provided in part 2 of this Supplementary Material.

2.SM.2.1 Reference card – AIM-CGE

About

⇨ ***Name and version***

⇨ ***Institution and users***

Model scope and methods

⇨ ***Objective***

⇨ ***Concept***

⇨ ***Solution method***

⇨ ***Anticipation***

⇨ ***Temporal dimension***
, time steps: **horizon:**
⇨ ***Spatial dimension***
Number of regions:

⇨ ***Policy implementation***

Socio economic drivers

⇨ ***Exogenous drivers***

–

⇨ ***Endogenous drivers***

–

⇨ ***Development***

–

Macro economy

⇨ ***Economic sectors***

–
–
–
–
–

⇨ ***Cost measures***

–
–
–

⇨ ***Trade***

–
–
–
–
–
–
–

Energy

⇨ ***Behaviour***

⇨ ***Resource use***

–
–
–
–

⇨ ***Electricity technologies***

–
–
–
–
–
–
–
–

⇨ ***Conversion technologies***

–
–

⇨ ***Grid and infrastructure***

⇨ ***Energy technology substitution***

–

⇨ ***Energy service sectors***

–
–
–

Land use

⇨ ***Land cover***

–
–
–
–
–

Other resources

Emissions and climate

⇨ ***Greenhouse gases***

–
–
–
–
–
–

⇨ ***Pollutants***

–
–
–
–
–
–

⇨ ***Climate indicators***

–
–
–

2.SM.2.2 Reference card – BET

About

- ⇨ ***Name and version***

- ⇨ ***Institution and users***

Role of end-use technologies in long-term GHG reduction scenarios developed with the BET model

Model scope and methods

- ⇨ ***Objective***

- ⇨ ***Concept***

- ⇨ ***Solution method***

- ⇨ ***Anticipation***

- ⇨ ***Temporal dimension***

, time steps: horizon:

- ⇨ ***Spatial dimension***

Number of regions:

- ⇨ ***Policy implementation***

Socio economic drivers

- ⇨ ***Exogenous drivers***

–
–
–

- ⇨ ***Endogenous drivers***

–

Macro economy

- ⇨ ***Economic sectors***
- ⇨ ***Cost measures***

–

–

–

- ⇨ ***Trade***

–

–

–

–

–

–

Energy

- ⇨ ***Behaviour***
- ⇨ ***Resource use***

–

–

–

–

–

–

–

- ⇨ ***Electricity technologies***

–

–

–

–

–

–

–

–

–

–

–

–

–

- ⇨ ***Conversion technologies***

–

–

–

–

–

–

- ⇨ ***Grid and infrastructure***

–

–

- ⇨ ***Energy technology substitution***

–

–

–

- ⇨ ***Energy service sectors***

–
–
–

Land use

- ⇨ ***Land cover***

–
–
–
–
–
–

Other resources

Emissions and climate

- ⇨ ***Greenhouse gases***

–

- ⇨ ***Pollutants***
- ⇨ ***Climate indicators***

–
–

2.SM.2.3 Reference card – C-ROADS

About

⇨ ***Name and version***

⇨ ***Institution and users***

Model scope and methods

⇨ ***Objective***

⇨ ***Concept***

⇨ ***Solution method***

⇨ ***Anticipation***

⇨ ***Temporal dimension***

, time steps: **horizon:**

⇨ ***Spatial dimension***

Number of regions:

⇨ ***Policy implementation***

Socio economic drivers

⇨ ***Exogenous drivers***

–

–

⇨ ***Endogenous drivers***

–

⇨ ***Development***
–

Macro economy
⇨ ***Economic sectors***
–
⇨ ***Cost measures***
–
⇨ ***Trade***
–

Energy

⇨ ***Behaviour***
–
⇨ ***Resource use***
–
⇨ ***Electricity technologies***
–
⇨ ***Conversion technologies***
–
⇨ ***Grid and infrastructure***
–
⇨ ***Energy technology substitution***
–
⇨ ***Energy service sectors***
–

Land use
⇨ ***Land cover***
–

Other resources
–

Emissions and climate
⇨ ***Greenhouse gases***
–
–
–
–
–
–
–
⇨ ***Pollutants***
–
⇨ ***Climate indicators***
–
–
–
–
–

2.SM.2.4 Reference card – DNE21

About

⇨ ***Name and version***

⇨ ***Institution and users***

Model scope and methods

⇨ ***Objective***
⇨ ***Concept***

⇨ ***Solution method***

⇨ ***Anticipation***

⇨ ***Temporal dimension***
Base year: , time steps: horizon:
⇨ ***Spatial dimension***
Number of regions:

⇨ ***Policy implementation***

Socio economic drivers

⇨ *Exogenous drivers*

–
–
–
–
–
–
–
–

Macro economy

⇨ *Economic sectors*

–
–
–
–

⇨ *Cost measures*

–

⇨ *Trade*

–
–
–
–
–

Energy

⇨ *Behaviour*

–
–
–
– Technology Adoption

⇨ *Resource use*

–
–
–
–
–

⇨ *Electricity technologies*

–
–
–
–
–
–
–
–
–
–
–
–
–

⇨ ***Conversion technologies***

–
–
–
–
–
–
–
–
–
–
–

⇨ ***Grid and infrastructure***

–
–
–
–

⇨ ***Energy technology substitution***

–
–

⇨ ***Energy service sectors***

–
–
–

Land use

⇨ ***Land cover***

–
–
–
–
–
–

Other resources

⇨ ***Other resources***

–

Emissions and climate

⇨ ***Greenhouse gases***

–
–
–
–
–
–

⇨ ***Pollutants***

–
–
–
–

⇨ ***Climate indicators***

–

–

–

2.SM.2.5 Reference card – FARM 3.2

About

⇨ ***Name and version***

⇨ ***Institution and users***

Model scope and methods

⇨ ***Objective***

⇨ ***Concept***

⇨ ***Solution method***

⇨ ***Anticipation***

⇨ ***Temporal dimension***

, time steps: **horizon:**

⇨ ***Spatial dimension***

Number of regions:

⇨ ***Policy implementation***

Socio economic drivers

⇨ ***Exogenous drivers***

–
–
–
–
–

⇨ ***Endogenous drivers***

–

⇨ ***Development***

–

Macro economy

⇨ ***Economic sectors***

–

–

–

–

⇨ ***Cost measures***

–

–

○

–

⇨ ***Trade***

–

–

–

–

–

–

Energy

⇨ ***Behaviour***

–

⇨ ***Resource use***

–

–

–

–

⇨ ***Electricity technologies***

–

–

–

–

–

–

–

⇨ ***Conversion technologies***

–

⇨ ***Grid and infrastructure***

–

–

–

⇨ ***Energy technology substitution***

–

⇨ ***Energy service sectors***

–

–

Land use

⇨ ***Land cover***

- –
    - ○
    - ○
    - ○
- –
- –

Other resources

⇨ ***Other resources***

–

Emissions and climate

⇨ ***Greenhouse gases***

–
- ○
- ○
- ○

⇨ ***Pollutants***

–

⇨ ***Climate indicators***

–

2.SM.2.6 Reference card – GCAM 4.2

About

- ***Name and version***
- ***Institution and users***

Model scope and methods

- ***Objective***
- ***Concept***
- ***Solution method***
- ***Anticipation***
- ***Temporal dimension***

, time steps: horizon:

- ***Spatial dimension***

Number of regions:

⇨ ***Policy implementation***

–
  ○
  ○
–
  ○
  ○
  ○
–
  ○
  ○
–
  ○
  ○

Socio economic drivers

⇨ ***Exogenous drivers***

–
–
–
–

⇨ ***Endogenous drivers***

–

⇨ ***Development***

–

Macro economy

⇨ ***Economic sectors***

–
–
–
–
–
–

⇨ ***Cost measures***

–

⇨ ***Trade***

–
–
–
–
–
–
–

Energy

⇨ ***Behaviour***

–

⇨ ***Resource use***

–
–
–
–
–
–
–
–

⇨ ***Electricity technologies***

–
–
–
–
–
–
–
–

⇨ ***Conversion technologies***

–
–
    –
    –
–
    –
    –
–
    –
    –
    –

⇨ ***Grid and infrastructure***

–

⇨ ***Energy technology substitution***

–

⇨ ***Energy service sectors***

–
–
–

Land use

⇨ ***Land cover***

  –
      ○
      ○
      ○
  –
      ○
      ○
  –
  –

- –
- –
- –

Other resources

⇨ ***Other resources***

–
–

Emissions and climate

⇨ ***Greenhouse gases***

–
–
–
–
–
–

⇨ ***Pollutants***

–
–
–
–
–

⇨ ***Climate indicators***

–
–
–

2.SM.2.7 Reference card – GEM-E3

About

- ⇨ ***Name and version***

- ⇨ ***Institution and users***

Model scope and methods

- ⇨ ***Objective***

- ⇨ ***Concept***

- ⇨ ***Solution method***

- ⇨ ***Anticipation***

- ⇨ ***Temporal dimension***

Base year: **time steps:** **horizon:**

- ⇨ ***Spatial dimension***

Number of regions:

Number of regions:

- ⇨ ***Policy implementation***

Socio economic drivers

- ⇨ ***Exogenous drivers***

–
–
–
–
–
–

- ⇨ ***Endogenous drivers***

–

⇨ ***Development***

–

–

Macro economy

⇨ ***Economic sectors***

–

–

–

–

–

–

⇨ ***Cost measures***

–

–

–

⇨ ***Trade***

–

–

–

–

–

–

–

–

–

–

–

–

–

–

Energy

⇨ ***Behaviour***

⇨ ***Resource use***

–
–
–
–

⇨ ***Electricity technologies***

–
–
–
–
–
–
–
–

⇨ ***Conversion technologies***

⇨ ***Grid and infrastructure***

–

⇨ ***Energy technology substitution***

–

⇨ ***Energy service sectors***

–
–
–

Land use

⇨ ***Land cover***

Other resources

⇨ ***Other resources***

Emissions and climate

⇨ ***Greenhouse gases***

–
–
–
–
–
–

⇨ ***Pollutants***

–
–

⇨ ***Climate indicators***

2.SM.2.8 Reference card – GENeSYS-MOD 1.0

About

- ⇨ ***Name and version***

- ⇨ ***Institution and users***

Model scope and methods

- ⇨ ***Objective***

- ⇨ ***Concept***

- ⇨ ***Solution method***

- ⇨ ***Anticipation***

- ⇨ ***Temporal dimension***

Base year: **time steps:** **horizon:**

- ⇨ ***Spatial dimension***

- ⇨ ***Policy implementation***

Socio economic drivers

- ⇨ ***Exogenous drivers***

–
–
–

- ⇨ ***Endogenous drivers***
- ⇨ ***Development***

Macro economy

- ⇨ ***Economic sectors***
- ⇨ ***Cost measures***
- ⇨ ***Trade***

Energy

- ⇨ ***Behaviour***
- ⇨ ***Resource use***

–
–
–
–
–

- ⇨ ***Electricity technologies***

–
–
–
–
–
–
–
–
–
–
–

- ⇨ ***Conversion technologies***

–
–
–

- ⇨ ***Grid and infrastructure***

–

- ⇨ ***Energy technology substitution***

–
–
–

- ⇨ ***Energy service sectors***

–
–
–

Land use

- ⇨ ***Land cover***

Other resources

- ⇨ ***Other resources***

Emissions and climate

- ⇨ ***Greenhouse gases***

–

- ***Pollutants***
- ***Climate indicators***

2.SM.2.9 Reference card – GRAPE-15 1.0

About

⇨ ***Name and version***

⇨ ***Institution and users***

Model scope and methods

⇨ ***Objective***

⇨ ***Concept***
⇨ ***Solution method***

⇨ ***Anticipation***

⇨ ***Temporal dimension***
, time steps: **horizon:**
⇨ ***Spatial dimension***
Number of regions:

⇨ ***Policy implementation***

Socio economic drivers

⇨ ***Exogenous drivers***
–
–
–
–
–
–
–
–
⇨ ***Endogenous drivers***
–
⇨ ***Development***
–

–

–

Macro economy

⇨ *Economic sectors*

–

–

–

–

–

⇨ *Cost measures*

–

–

–

–

⇨ *Trade*

–

–

–

–

–

–

–

Energy

⇨ *Behaviour*

–

⇨ *Resource use*

–

–

–

–

–

–

–

–

–

⇨ *Electricity technologies*

–

–

–

–

–

–

–

–

–

⇨ *Conversion technologies*

–

–

–

  –

  –

    –
    –
    –
    –
–
    –
–
    –
    –
    –
    –

⇨ ***Grid and infrastructure***

–
–
–
–
–

⇨ ***Energy technology substitution***

–
–

⇨ ***Energy service sectors***

–
–
–

Land use

⇨ ***Land cover***

–
–
–
–

Other resources

⇨ ***Other resources***

–

Emissions and climate

⇨ ***Greenhouse gases***

–
    ○
    ○
–
    ○
    ○
–
    ○
–
–
–
–
    ○

⇨ ***Pollutants***

–
–
–
–
–

⇨ ***Climate indicators***

–
–
–

2.SM.2.10 Reference card – ETP Model

About

- ***Name and version***

- ***Institution and users***

Model scope and methods

- ***Objective***

- ***Concept***

- ***Solution method***

- ***Anticipation***

- ***Temporal dimension***

, time steps: horizon:

- ***Spatial dimension***

Number of regions:

- ***Policy implementation***

Socio economic drivers

- ***Exogenous drivers***

–

–
–
–
- ⇨ ***Endogenous drivers***

–
- ⇨ ***Development***

–

Macro economy

- ⇨ ***Economic sectors***

–
–
–
–
–
–
–
- ⇨ ***Cost measures***

–
- ⇨ ***Trade***

–
–
–
–

Energy

- ⇨ ***Behaviour***

–
- ⇨ ***Resource use***

–
–
–
–
–
–
- ⇨ ***Electricity technologies***

–
–
–
–
–
–
–
–
–
- ⇨ ***Conversion technologies***

–
–
–
–
–
–
–

–
–
–
–
–
–
–
–
–
–
–

⇨ ***Grid and infrastructure***

–
–
–
–
–
–

⇨ ***Energy technology substitution***

–

–
–

⇨ ***Energy service sectors***

–
–
–

Land use

⇨ ***Land cover***

–

Other resources

⇨ ***Other resources***

–

Emissions and climate

⇨ ***Greenhouse gases***

–
–

⇨ ***Pollutants***

–

⇨ ***Climate indicators***

–

2.SM.2.11 Reference card – IEA World Energy Model

About

- ⇨ ***Name and version***
- ⇨ ***Institution and users***

Model scope and methods

- ⇨ ***Objective***
- ⇨ ***Concept***
- ⇨ ***Solution method***
- ⇨ ***Anticipation***
- ⇨ ***Temporal dimension***
- ⇨ ***Spatial dimension***
- ⇨ ***Policy implementation***

Socio economic drivers

⇨ ***Exogenous drivers***

–
–
–

⇨ ***Endogenous drivers***

–

⇨ ***Development***

Macro economy

⇨ ***Economic sectors***

–
–
–
–

⇨ ***Cost measures***

–

⇨ ***Trade***

–
–
–
–
–

Energy

⇨ ***Behaviour***

⇨ ***Resource use***

–
–
–
–
–
–

⇨ ***Electricity technologies***

–
–
–
–
–
–
–
–
–
–
–
–

⇨ ***Conversion technologies***

–
–
–
–

–
–
–
–
–
–

⇨ ***Grid and infrastructure***

–
–

⇨ ***Energy technology substitution***

–
–
–

–
–

⇨ ***Energy service sectors***

–
–
–

Land use

⇨ ***Land cover***

-

Other resources

⇨ ***Other resources***

Emissions and climate

⇨ ***Greenhouse gases****

–
–
–
–
–
–

⇨ ***Pollutants****

–
–
–
–
–
–
–

⇨ ***Climate indicators***

–
–
–

2.SM.2.12 Reference card – IMACLIM

About

⇨ ***Name and version***

⇨ ***Institution and users***

Model scope and methods

⇨ ***Objective***

⇨ ***Concept***

⇨ ***Solution method***

⇨ ***Anticipation***

⇨ ***Temporal dimension***

, time steps: horizon:

⇨ ***Spatial dimension***

Number of regions:

⇨ ***Policy implementation***

Socio economic drivers

⇨ ***Exogenous drivers***

–

–

–

–

⇨ ***Endogenous drivers***
⇨ ***Development***
–

Macro economy

⇨ ***Economic sectors***
–
–
–
– *Transport*
– *Services*
– *Construction*

⇨ ***Cost measures***
–
–
–
–
⇨ ***Trade***
–
–
–
–
–
–
–
–
–

Energy

⇨ ***Behaviour***

⇨ ***Resource use***
–
–
–
–
⇨ ***Electricity technologies***
–
–
–
–
–

–
–
–
⇨ ***Conversion technologies***
–
⇨ ***Grid and infrastructure***
–
⇨ ***Energy technology substitution***
–
–
–
⇨ ***Energy service sectors***
–
–
–
–

Land use
⇨ ***Land cover***
–
–
–
–
–
–
–

Other resources
⇨ ***Other resources***

Emissions and climate
⇨ ***Greenhouse gases***
•
⇨ ***Pollutants***
⇨ ***Climate indicators***

2.SM.2.13 Reference card – IMAGE

About

⇨ ***Name and version***

⇨ ***Institution and users***

Model scope and methods

⇨ ***Objective***

⇨ ***Concept***

⇨ ***Solution method***

⇨ ***Anticipation***

⇨ ***Temporal dimension***

, time steps: **horizon:**

⇨ ***Spatial dimension***

Number of regions:

⇨ ***Policy implementation***

–
–
–
–
–

Socio economic drivers

⇨ ***Exogenous drivers***

–
–
–

⇨ ***Endogenous drivers***

–
–
–
–
–
–
–
–
–
–

⇨ ***Development***

–
–
–

Macro economy

⇨ ***Economic sectors***

⇨ ***Cost measures***

–
–

⇨ ***Trade***

–
–
–
–
–
–
–
–
–

–

Energy

⇨ *Behaviour*

⇨ *Resource use*

–
–
–
–
–

⇨ *Electricity technologies*

–
–
–
–
–
–
–
–
–
–
–
–
–
–

⇨ *Conversion technologies*

–
–

⇨ *Grid and infrastructure*

–

⇨ *Energy technology substitution*

–
–
–

⇨ *Energy service sectors*

–
–
–

Land use

⇨ *Land cover*

–
–

–
–
–

Other resources

⇨ *Other resources*

–
–
–

Emissions and climate

⇨ *Greenhouse gases*

–
–
–
–
–
–
–

⇨ *Pollutants*

–
–
–
–
–
–
–
–

⇨ *Climate indicators*

–
–
–

2.SM.2.14 Reference card – MERGE-ETL 6.0

About

⇨ ***Name and version***

⇨ ***Institution and users***

Model scope and methods

⇨ ***Objective***

⇨ ***Concept***

⇨ ***Solution method***

⇨ ***Anticipation***

⇨ ***Temporal dimension***

, time steps: **horizon:**

⇨ ***Spatial dimension***

Number of regions:

⇨ ***Policy implementation***

Socio economic drivers

⇨ ***Exogenous drivers***

⇨ ***Development***

GDP

Macro economy

⇨ ***Economic sectors***

–

–

⇨ ***Cost measures***

–

–

–

–

–

⇨ ***Trade***

–

–

–

–

–

–

–

Energy

⇨ ***Behaviour***

–

⇨ ***Resource use***

–

–

–

–

–

–

–

⇨ ***Electricity technologies***

–

–

–

–

–

–

–

–

⇨ ***Conversion technologies***

–

–

⇨ ***Grid and infrastructure***

–

–
–
–

⇨ ***Energy technology substitution***

–
–
–

⇨ ***Energy service sectors***

–

Land use

⇨ ***Land cover***

Other resources

⇨ ***Other resources***

Emissions and climate

⇨ ***Greenhouse gases***

–
–
–
–
–

⇨ ***Pollutants***

⇨ ***Climate indicators***

–
–
–
–

2.SM.2.15 Reference card – MESSAGE(ix)-GLOBIOM

About

⇨ ***Name and version***

ix

⇨ ***Institution and users***

ix

ix

Model scope and methods

⇨ ***Objective***

⇨ ***Concept***

⇨ ***Solution method***

⇨ ***Anticipation***

⇨ ***Temporal dimension***

Base year: **time steps:**
horizon:

⇨ ***Spatial dimension***

⇨ ***Policy implementation***

Socio economic drivers

⇨ ***Exogenous drivers***

–

–

–
–
⇨ ***Endogenous drivers***
⇨ ***Development***
–
–
–

Macro economy

⇨ ***Economic sectors***

⇨ ***Cost measures***
–
–
–
–
⇨ ***Trade***
–
–
–
–
–
–
–

Energy

⇨ ***Behaviour***

⇨ ***Resource use***
–
–
–
–
–

⇨ ***Electricity technologies***
–
–
–
–
–
–
–
–
–
–
–
– *CSP*

– *Geothermal*
– *Hydropower*

⇨ ***Conversion technologies***
–
–
–
–

⇨ ***Grid and infrastructure***
–
–
–
–
–

⇨ ***Energy technology substitution***
–
–
–

⇨ ***Energy service sectors***
–
–
–

Land use

⇨ ***Land cover***
•
•
•
•
•

Other resources

⇨ ***Other resources***
–
–

Emissions and climate

⇨ ***Greenhouse gases***
–
–
–
–
–
–

⇨ ***Pollutants***
–

–
–
–
– *CO*
– *NH3*
– *VOC*

⇨ ***Climate indicators***

–
–
–

2.SM.2.16 Reference card – POLES

About

⇨ ***Name and version***

⇨ ***Institution and users***

Model scope and methods

⇨ ***Objective***

⇨ ***Concept***

⇨ ***Solution method***

⇨ ***Anticipation***

⇨ ***Temporal dimension***

Base year: , time steps: horizon:

⇨ ***Spatial dimension***

Number of regions:

⇨ ***Policy implementation***

Socio economic drivers

⇨ ***Exogenous drivers***

–

–

⇨ ***Endogenous drivers***

–

–

–

–

⇨ ***Development***

–

–

Macro economy

⇨ ***Economic sectors***

–

–

–

⇨ ***Cost measures***

–

–

⇨ ***Trade***

–
–
–
–
–
–

Energy

⇨ ***Behaviour***

⇨ ***Resource use***

–
–
–
–
–

⇨ ***Electricity technologies***

–
–
–
–
–
–
–
–
–
–
–
–

⇨ ***Conversion technologies***

–
–
–

⇨ ***Grid and infrastructure***

–
–

⇨ ***Energy technology substitution***

⇨ ***Energy service sectors***

–
–
–

Land use

⇨ ***Land cover***

–
–
–
–
–

Other resources

- ⇨ ***Other resources***

–

Emissions and climate

- ⇨ ***Greenhouse gases***

–

–

–

–

–

–

- ⇨ ***Pollutants***
- ⇨ ***Climate indicators***

2.SM.2.17 Reference card – REMIND - MAgPIE

About

⇨ ***Name and version***

⇨ ***Institution and users***

Model scope and methods

⇨ ***Objective***

REMIND

MAgPIE

⇨ ***Concept***

•

•

⇨ ***Solution method***

•

•

⇨ ***Anticipation***

•

•

⇨ ***Temporal dimension***

• **, time steps:**

•

⇨ ***Spatial dimension***

Number of regions:

⇨ ***Policy implementation***

-

-

Socio economic drivers

⇨ ***Exogenous drivers***

–

–

⇨ ***Endogenous drivers***

-

-

⇨ ***Development***

–

Macro economy (REMIND)

⇨ ***Economic sectors***

⇨ ***Cost measures***

–

–

–

⇨ ***Trade***

–

–

–

–

–

–

–

–

Energy (REMIND)

⇨ ***Behaviour***

Price response through CES production function. No explicit modelling of behavioural change. Baseline energy demands are calibrated in such a way that the energy demand patterns in different regions slowly converge when displayed as per capita energy demand over per capita GDP"

⇨ ***Resource use***

–

–

–

–

–

⇨ ***Electricity technologies***
–
–
–
–
–
–
–
–
– *Solar CSP*
– *Hydropower*
– *Geothermal*

⇨ ***Conversion technologies***
–
–
–
–
–
– *Heat plants*

⇨ ***Grid and infrastructure***
–
–
–
–
–

⇨ ***Energy technology substitution***
–
–
–

⇨ ***Energy service sectors***
–
–
–

<u>Land use (MAgPIE)</u>

Other resources

⇨ *Other resources*

–

Emissions and climate

⇨ *Greenhouse gases*

–
–
–
–
–
–

⇨ *Pollutants*

–
–
–
–
–
– *CO*
– *VOC*

⇨ *Climate indicators*

–
–
–

2.SM.2.18 Reference card – Shell - World Energy Model

About

⇨ ***Name and version***

⇨ ***Institution and users***

Model scope and methods

⇨ ***Objective***

⇨ ***Concept***

⇨ ***Solution method***

⇨ ***Anticipation***

⇨ ***Temporal dimension***

⇨ ***Spatial dimension***

Number of regions:

⇨ ***Policy implementation***

Socio economic drivers

⇨ ***Exogenous drivers***

–

–

⇨ ***Endogenous drivers***

⇨ ***Development***

Macro economy

⇨ ***Economic sectors***

–

–

–

–

⇨ ***Cost measures***

⇨ ***Trade***

–

–

–

–

Energy

⇨ ***Behaviour***

⇨ ***Resource use***

–

–

–

–
–
–
⇨ ***Electricity technologies***
–
–
–
–
–
–
–
–
–
–
⇨ ***Conversion technologies***
–
–
–
–
–
–
–
–
–
–
–
–
–
–
–
–
–
–
–
⇨ ***Grid and infrastructure***
⇨ ***Energy technology substitution***
–
–
–

–
⇨ ***Energy service sectors***
–
–
–

Land use

- ⇨ ***Land cover***

Other resources

- ⇨ ***Other resources***

Emissions and climate

- ⇨ ***Greenhouse gases***

–

- ⇨ ***Pollutants***
- ⇨ ***Climate indicators***

2.SM.2.19 Reference card – WITCH

About

⇨ ***Name and version***

⇨ ***Institution and users***

Model scope and methods

⇨ ***Objective***

⇨ ***Concept***

⇨ ***Solution method***

⇨ ***Anticipation***

⇨ ***Temporal dimension***

, time steps:5 horizon:

⇨ ***Spatial dimension***

Number of regions:

⇨ ***Policy implementation***

Socio economic drivers

⇨ ***Exogenous drivers***

–

–

–

⇨ ***Development***

Macro economy

⇨ ***Economic sectors***

–
–

⇨ ***Cost measures***

–
–
–
–

⇨ ***Trade***

–
–
–
–

Energy

⇨ ***Resource use***

–
–
–
–
–

⇨ ***Electricity technologies***

–
–
–
–
–
–
–
–

⇨ ***Conversion technologies***

⇨ ***Grid and infrastructure***

–
–

⇨ ***Energy technology substitution***

–
–

⇨ ***Energy service sectors***

–

Land use

⇨ ***Land cover***

–
–

Other resources

⇨ *Other resources*

–

Emissions and climate

⇨ *Greenhouse gases*

–
–
–
–
–
–

⇨ *Pollutants*

–
–
–
–

⇨ *Climate indicators*

–
–
–
–