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Mitigation Pathways Compatible with 1.5°C in the Context of Sustainable Development

Supplementary Material

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This chapter supplementary material should be cited as:

Forster, P., D. Huppmann, E. Kriegler, L. Mundaca, C. Smith, J. Rogelj, and R. Séférian, 2018: Mitigation Pathways Compatible with 1.5°C in the Context of Sustainable Development Supplementary Material. In: *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty* [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (eds.)]. Available from https://www.ipcc.ch/sr15

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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 models for lower emissions 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 uncertainty in the pathway classification approach and to support the carbon budget evaluation (Chapter 2, Section 2.2 and 2.SM.1.1.2).

This 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 parametrization 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). MAGICC has a weaker CH_4 radiative forcing, but 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.

The transient climate response to cumulative carbon emissions (TCRE) differences between the models are an informative illustration of their parametric differences (Figure 2.SM.3). In the setups used in this report, FAIR has a TCRE median of 0.38°C (5–95% range of 0.25°C to 0.57°C) per 1000 GtO_2 and MAGICC a TCRE median of 0.47°C (5–95% range of 0.13°C 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°C to 0.7°C per 1000 $GtCO_2$ (Collins et al., 2013) (see Section 2.SM.1.1.2).

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 this 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.

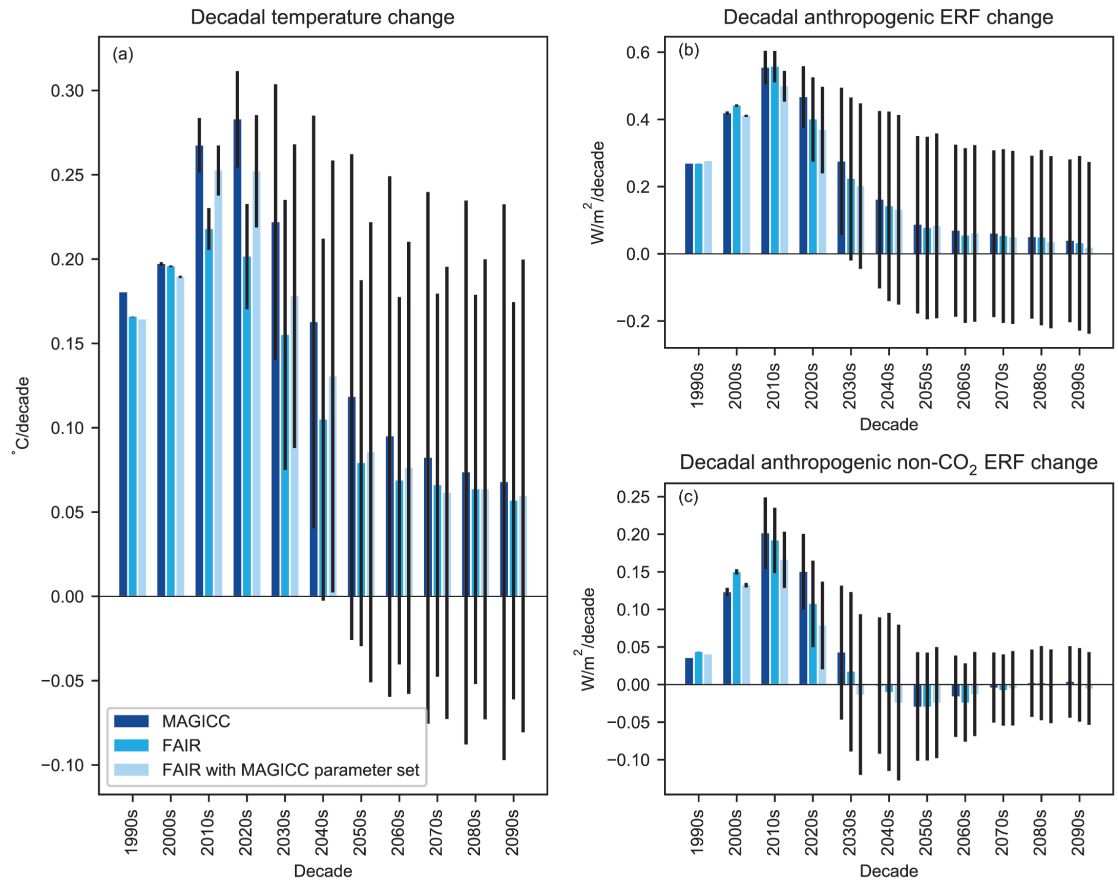

Figure 2.SM.1 | Warming rates per decade for MAGICC (dark blue), FAIR (sky blue) and FAIR matching the MAGICC parameter set (light blue) for the scenario dataset used in this report. These bars represent the mean of regression slopes taken over each decade (years 0 to 9) for scenario median temperature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

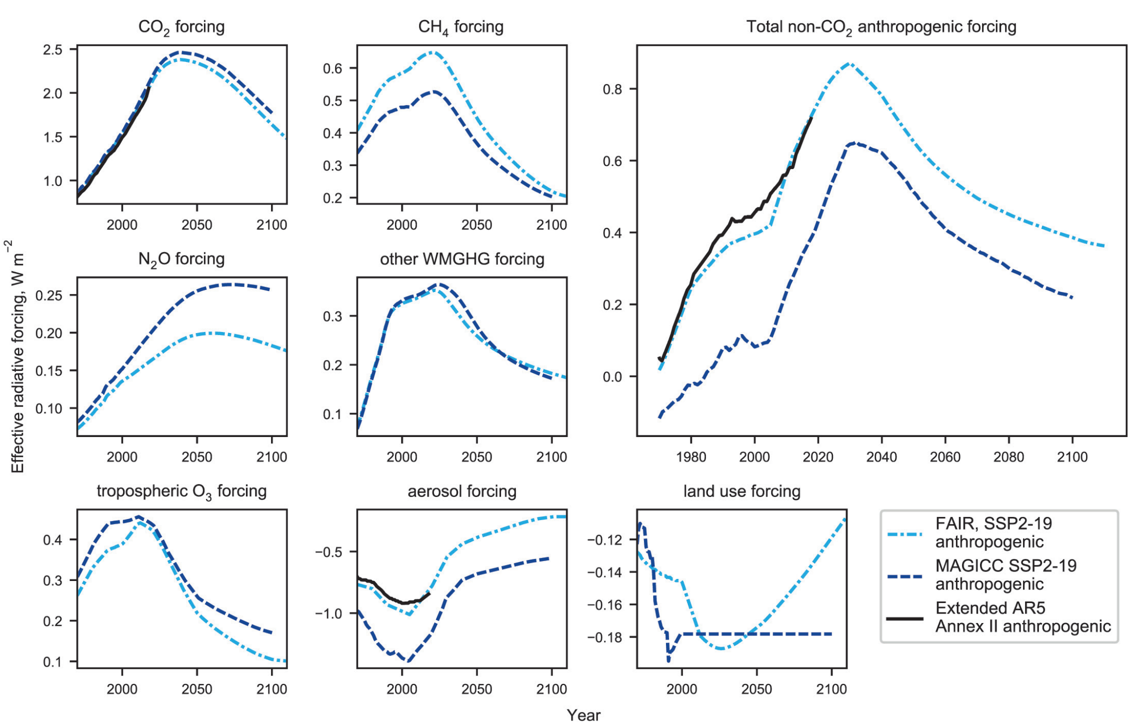

Figure 2.SM.2 | Time series of MAGICC (dark blue dashed) and FAIR (sky blue dash-dotted) effective radiative forcing for an example emission scenario for the main forcing agents where the models exhibit differences. AR5 data is from Myhre et al. (2013), extended from 2011 until the end of 2017 with greenhouse 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 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.

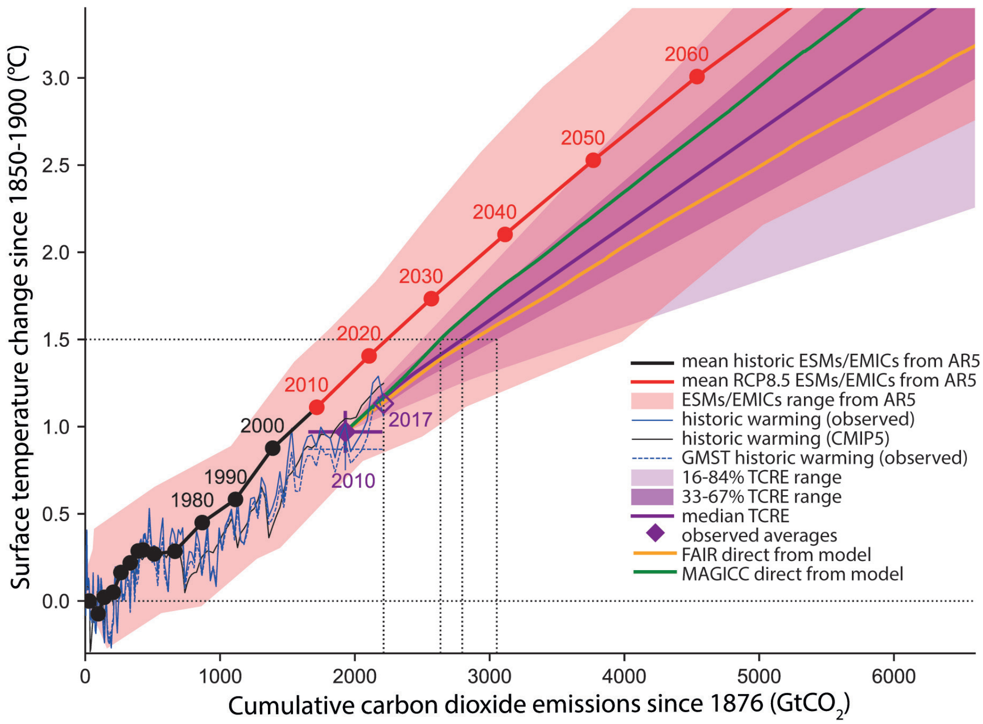

Figure 2.SM.3 | This figure follows Figure 2.3 of the main report but with two extra lines showing FAIR (orange) and MAGICC (green) results separately. These additional lines show the full model response averaged across all scenarios and geophysical parameters.

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 42 ± 3 GtCO2 yr^{-1} (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) have 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, 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 predefined levels of future peak warming (ΔT_{peak}) between 0.3°C and 1.2°C. The CO_2-only carbon budget is subsequently computed for this revised set of warming levels (ΔT_{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.

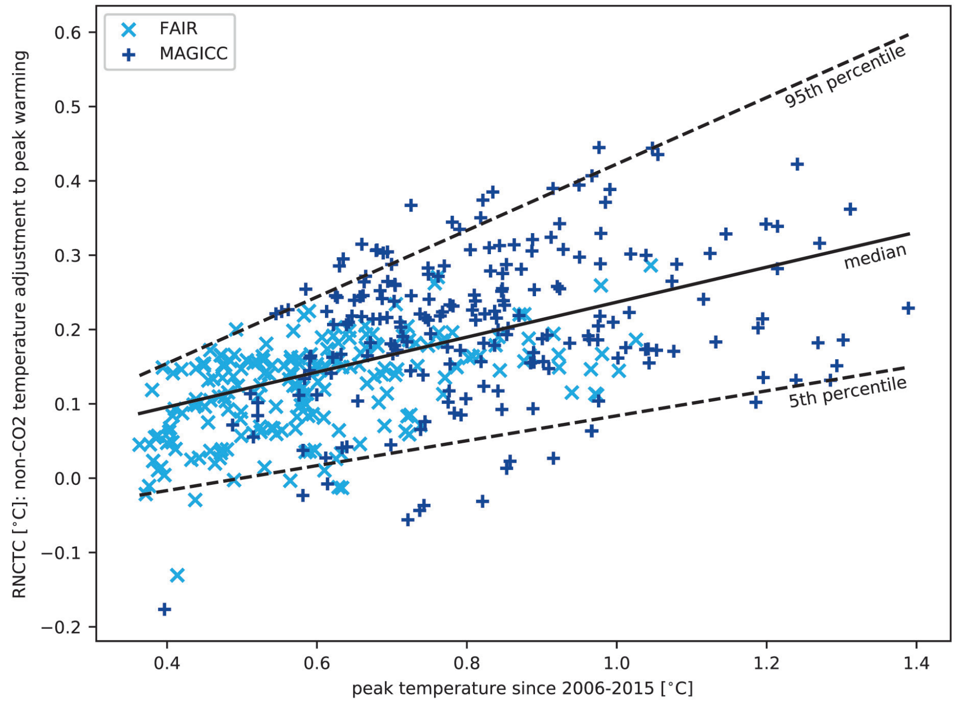

Figure 2.SM.4 | Relationship of RNCTC with peak temperature in the FAIR and MAGICC models. The black line is the linear regression relationship between peak temperature and RNCTC. The dashed lines show the quantile regressions at the 5th and 95th percentile.

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°C 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 from 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 $GtCO_2$.

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 ($\Delta F_{non\text{-}CO2}$) and the Absolute Global Warming Potential of CO_2 ($AGWP_H(CO_2)$) over time horizon H, taken to be 100 years:

$$\Delta T_{peak} \approx TCRE \times (G_{CO2} + \Delta F_{non\text{-}CO2} \times (H/AGWP_H(CO_2)) \qquad (2.SM.1)$$

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 $\Delta F_{non\text{-}CO2}$ in Equation 2.SM.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}) and the results showed 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 are 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.1 | Remaining CO_2-only budget in $GtCO_2$ from 1 January 2018 for different levels of warming from 2006–2015 for normal and log-normal distributions of TCRE based on the AR5 likely range. 290 $GtCO_2$ have 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 standard deviation uncertainty range of ±0.12°C.

	Normal Distribution			Log-Normal Distribution		
CO_2-only Remaining Budgets ($GtCO_2$)	TCRE 0.35°C per 1000 $GtCO_2$	TCRE 0.45°C per 1000 $GtCO_2$	TCRE 0.55°C per 1000 $GtCO_2$	TCRE 0.30°C per 1000 $GtCO_2$	TCRE 0.38°C per 1000 $GtCO_2$	TCRE 0.50°C per 1000 $GtCO_2$
Additional warming from 2005–2015 °C	TCRE 33%	TCRE 50%	TCRE 67%	TCRE 33%	TCRE 50%	TCRE 67%
0.3	571	376	253	709	487	315
0.4	859	598	434	1042	746	517
0.5	1146	820	615	1374	1005	718
0.6	1433	1042	796	1707	1265	920
0.7	1720	1264	977	2040	1524	1122
0.8	2007	1486	1158	2373	1783	1323
0.9	2294	1709	1339	2706	2042	1525
1	2581	1931	1520	3039	2301	1726
1.1	2868	2153	1701	3372	2560	1928
1.2	3156	2375	1882	3705	2819	2130

Table 2.SM.2 | Remaining carbon dioxide budget from 1 January 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 $GtCO_2$ have 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.

		MAGICC				FAIR		
Remaining Carbon Budgets ($GtCO_2$) Additional warming from 2006–2015 °C	**MAGICC RNCTC** (°C)	TCRE 33%	TCRE 50%	TCRE 67%	**FAIR RNCTC** (°C)	TCRE 33%	TCRE 50%	TCRE 67%
0.3	0.14	184	77	9	0.06	402	245	146
0.4	0.15	434	270	166	0.08	629	421	289
0.5	0.16	681	461	322	0.10	856	596	433
0.6	0.18	930	654	480	0.12	1083	772	576
0.7	0.19	1177	845	635	0.14	1312	949	720
0.8	0.20	1427	1038	793	0.16	1539	1125	863
0.9	0.22	1674	1229	948	0.18	1766	1300	1006
1	0.23	1924	1422	1106	0.20	1993	1476	1149
1.1	0.24	2171	1613	1262	0.22	2223	1653	1294
1.2	0.26	2421	1806	1419	0.25	2449	1829	1437

Table 2.SM.3 | Remaining carbon dioxide budgets from 1 January 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 $GtCO_2$ have been removed to account for emissions between the start of 2011 and the end of 2017.

		FAIR		
Remaining Carbon Budgets ($GtCO_2$) Additional warming from 2006–2015 °C	**FAIR RNCFC** (Wm^{-2})	TCRE 33%	TCRE 50%	TCRE 67%
0.3	0.191	363	168	45
0.4	0.211	629	368	204
0.5	0.232	893	568	362
0.6	0.253	1157	767	521
0.7	0.273	1423	967	680
0.8	0.294	1687	1166	838
0.9	0.314	1952	1366	997
1	0.335	2216	1566	1155
1.1	0.356	2481	1765	1314
1.2	0.376	2746	1965	1473

2.SM.1.1.2.3 Uncertainties

Uncertainties are explored across several lines of evidence and summarized in Table 2.2 of the main report. Expert judgement is used to estimate the overall uncertainty and to estimate the amount of 100 $GtCO_2$ that is removed to account for possible missing permafrost and wetlands feedbacks (see Section 2.2). Irrespective of the metric used to estimate global warming, the uncertainty in global warming since pre-industrial levels (1850–1900) up to the 2006–2015 reference period as estimated in Chapter 1 is of the order of ±0.1°C (*likely* range). This uncertainty affects how close warming since pre-industrial levels is to the 1.5°C and 2°C limits. To illustrate this impact, the remaining carbon budgets for a range of future warming thresholds between 0.3°C 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.

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A measure of the uncertainty due to variations in the consistent level of non-CO_2 mitigation at the time that 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 were 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.

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 contribute 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 in this report are approximately 290 $GtCO_2$ with an uncertainty of about 20 $GtCO_2$.

Table 2.SM.4 | Remaining carbon dioxide budget from 1 January 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.A.1). 290 $GtCO_2$ have 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.

	Log-Normal Minus Normal TCRE Distribution		
Remaining Budgets ($GtCO_2$) Additional warming from 2006–2015 °C	TCRE 33%	TCRE 50%	TCRE 67%
0.3	110	89	50
0.4	146	118	66
0.5	183	148	82
0.6	219	177	99
0.7	255	207	115
0.8	291	236	131
0.9	328	265	148
1	364	294	164
1.1	400	324	180
1.2	436	353	197

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 sectoral 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 (van Sluisveld et al., 2016; McCollum et al., 2017; 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., 2019), 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 harmonized model documentation of IAMs and underlying assumptions has been established within the framework of the EU ADVANCE project, which is available at www.iamcdocumentation.eu

2.SM.1.2.1 Short Introduction to the Scope, Use and Limitations of Integrated Assessment Modelling

IAMs are characterized 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. This allows them to identify the 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 a price needs to be distinguished from suggested levels of emissions pricing in multidimensional policy contexts that are adapted to existing market environments and often include a portfolio of policy instruments (Chapter 2, 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, mainly for 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 biophysical 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, such as agriculture (Stevanović et al., 2016), these IAMs do not take into account climate impacts as a whole in their pathway modelling. The 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 (Chapter 2, Section 2.6) and are a 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 Supplementary Material 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 (Section 2.SM.1.2.5). Another important aspect for the use of IAMs in solution-oriented assessments is building trust 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 idealized policy conditions which assume that climate change mitigation measures are undertaken where and when they are the most effective (Clarke et al., 2014). Such 'idealized implementation' scenarios assume that a global price on GHG emissions is implemented across all countries and all economic sectors, and rises over time through 2100 in a way that will minimize discounted economic costs. The emissions price reflects marginal abatement costs and is often used as a proxy of climate policy costs (see Chapter 2, 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, idealized 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, Section 4.4). Scenarios from idealized conditions provide benchmarks for policymakers, since deviations from the idealized approaches capture important challenges for socio-technical and economic systems and resulting climate outcomes.

Model experiments diverging from idealized 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 policy regimes in which some regions champion immediate climate mitigation action (e.g., by 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 GWP100) 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.

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 to which 13 out of 19 teams responded, discount rate assumptions varied between 2% yr^{-1} and 8% yr^{-1} 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 the fact 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 a 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, resulting in higher overall mitigation costs compared to a case with globally uniform discounting (Iyer et al., 2015). More work is also 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, 2007; 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 non-linear 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, Section 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). Predetermining 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-minimization 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; Geels et al., 2017; McCollum 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 is 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 (Chapter 2, 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 (alternative) baseline(s). 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 are based on the SSPs (Popp et al., 2017; Riahi et al., 2017) and all include an explicit land model. These land models calculate the supply of food, feed, fibre, 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 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 subsidies affecting bioenergy profits), and the demand for land for other purposes. Dominant bioenergy feedstocks assumed in IAMs are woody and grassy energy crops (second-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 depends 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 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

Table 2.SM.5 | Land-use type 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 rang land. 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

the carbon uptake from growing bioenergy and the emissions from combusting bioenergy (assuming it is not combined with CCS).

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 www.iamcdocumentation.eu (last accessed on 15 May 2018) and updated. These reference cards are provided in part 2 of this Supplementary Material.

2.SM.1.2.6 Overview of Mitigation Measures in Contributed IAM Scenarios

Table 2.SM.6 | Overview of the 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 agriculture forestry and other land-use (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.

Levels of Inclusion

	Explicit	Implicit
Endogenous	A	C
Exogenous	B	D
E	Not represented by model	

Levels of Inclusion	AIM	BET	COPPE-COFFEE	C-ROADS	DNE21+	GCAM 4.2	GEM-E3 3.0	GENESYSmod 1.0	GRAPE 1.0	IEA ETP	IEA WEM	IMACLIM 1.1	IMACLIM NL	IMAGE 3.0	MERGE-ETL 6.0	MESSAGE-GLOBIOM	MESSAGEix-GLOBIOM	POLES	REMIND-MAgPIE	Shell WEM v1	WITCH
Demand Side Measures																					
Energy efficiency improvements in energy end uses (e.g., appliances in buildings, engines in transport, industrial processes)	A	A	C	D	B	D	B	D	B	A	A	A	A	A	C	C	B	C	C	B	C
Electrification of transport demand (e.g., electric vehicles, electric rail)	A	A	A	D	A	A	B	A	A	A	A	A	A	A	C	A	A	A	A	B	A
Electrification of energy demand for buildings (e.g., heat pumps, electric/induction stoves)	A	A	A	D	A	A	B	A	D	A	A	C	C	A	C	A	A	A	C	B	C
Electrification of industrial energy demand (e.g., electric arc furnace, heat pumps, electric boilers, conveyor belts, extensive use of motor control, induction heating, industrial use of microwave heating)	A	A	C	D	A	C	D	A	D	A	A	C	C	A	C	A	A	C	C	B	C
CCS in industrial process applications (cement, pulp and paper, iron steel, oil and gas refining, chemicals)	A	E	A	D	D	A	E	E	C	A	A	E	E	A	E	A	A	E	A	B	C
Higher share of useful energy in final energy (e.g., insulation of buildings, lighter weight vehicles, combined heat and power generation, district heating, etc)	C	E	C	D	A	C	D	D	C	B	B	D	D	A	C	A	A	A	C	D	C
Reduced energy and service demand in **industry** (e.g., process innovations, better control)	C	C	C	D	C	C	C	D	D	B	B	C	C	B	C	C	B	B	C	C	C
Reduced energy and service demand in **buildings** (e.g., via behavioural change, reduced material and floor space demand, infrastructure and buildings configuration)	C	C	C	D	C	C	C	D	D	C	C	D	D	C	C	C	B	B	C	C	C
Reduced energy and service demand in **transport** (e.g., via behavioural change, new mobility business models, modal shift in individual transportation, eco-driving, car/bike-sharing schemes)	C	C	C	D	C	A	B	D	B	B	C	C	C	C	C	C	B	B	C	C	C
Reduced energy and service demand in **international transport** (international shipping and aviation)	A	E	A	D	D	A	C	E	B	B	B	C	C	C	C	B	B	A	D	C	C
Reduced material demand via higher resource efficiency, structural change, behavioural change and material substitution (e.g., steel and cement substitution, use of locally available building materials)	A	E	E	D	D	D	C	E	D	B	B	E	E	B	E	D	B	E	C	C	C
Urban form (including integrated on-site energy, influence of avoided transport and building energy demand)	E	E	E	D	D	E	E	D	E	B	E	D	D	E	E	E	B	E	E	C	E
Switch from traditional biomass and solid fuel use in the residential sector to modern fuels, or enhanced combustion practices, avoiding wood fuel	D	A	A	D	D	B	E	A	A	A	A	E	E	A	E	A	A	B	D	C	A
Dietary changes, reducing meat consumption	A	E	E	D	D	A	E	E	B	E	E	E	B	B	E	B	B	B	B	E	E
Substitution of livestock-based products with plant-based products (cultured meat, algae-based fodder)	C	E	E	D	E	E	E	E	E	E		E	B	B	E	E	E	E	E	E	E
Food processing (e.g., use of renewable energies, efficiency improvements, storage or conservation)	C	E	E	D	E	E	E	E	E	C	C	E	E	E	E	B	B	E	D	E	E
Reduction of food waste (including reuse of food processing refuse for fodder)	B	E	E	D	E	D	E	E	E	E	E	E	D	B	E	B	B	E	B	E	E
Supply Side Measures																					
Decarbonisation of Electricity:																					
Solar PV	A	A	A	D	A	A	B	A	A	A	A	A	A	A	A	A	A	A	A	A	A
Solar CSP	E	E	A	D	E	A	E	A	E	A	A	A	A	A	A	A	A	A	A	A	A

Table 2.SM.6 (continued)

Levels of Inclusion			Model Names																				
	Explicit	Implicit	AIM	BET	COPPE-COFFEE	C-ROADS	DNE21+	GCAM 4.2	GEM-E3 3.0	GENESYSmod 1.0	GRAPE 1.0	IEA ETP	IEA WEM	IMACLIM 1.1	IMACLIM NL	IMAGE 3.0	MERGE-ETL 6.0	MESSAGE-GLOBIOM	MESSAGEix-GLOBIOM	POLES	REMIND-MAgPIE	Shell WEM v1	WITCH
Endogenous	A	C																					
Exogenous	B	D																					
E	Not represented by model																						
Supply Side Measures																							
Decarbonisation of Electricity:																							
Wind (on-shore and off-shore)			A	A	A	D	A	A	B	A	A	A	A	A	A	A	A	A	A	A	A	A	A
Hydropower			A	A	A	D	A	A	B	A	A	A	A	A	A	B	A	A	A	A	A	A	A
Bio-electricity, including biomass co-firing			A	A	A	D	A	A	B	A	A	A	A	A	A	A	A	A	A	A	A	A	A
Nuclear energy			A	A	A	D	A	A	B	A	A	A	A	A	A	A	A	A	A	A	A	A	A
Advanced, small modular nuclear reactor designs (SMR)			E	E	A	D	E	A	E	E	E	C	C	E	E	E	A	E	E	E	E	C	E
Fuel cells (hydrogen)			E	E	A	D	A	A	E	A	A	A	A	E	E	A	A	A	A	A	A	A	A
CCS at coal and gas-fired power plants			A	A	A	D	A	A	B	E	A	A	A	A	A	A	A	A	E	A	A	B	A
Ocean energy (including tidal and current energy)			E	E	E	D	E	E	D	A	E	A	A	E	E	E	E	E	E	A	E	A	E
High-temperature geothermal heat			A	B	A	D	A	A	D	E	A	A	A	E	E	B	E	A	A	A	E	C	E
Decarbonisation of Non-Electric Fuels:																							
Hydrogen from biomass or electrolysis			E	A	A	D	A	A	E	A	A	A	C	E	E	A	A	A	A	A	A	A	E
First generation biofuels			A	E	A	D	A	A	B	E	A	A	A	C	A	A	A	B	B	A	B	A	A
Second generation biofuels (grassy or woody biomass to liquids)			A	A	A	D	A	A	B	A	A	A	A	E	A	A	A	A	A	A	A	A	A
Algae biofuels			E	E	A	D	E	E	E	C	E	E	C	E	E	E	E	E	E	E	E	A	E
Power-to-gas, methanisation, synthetic fuels			E	C	A	D	A	E	E	A	E	E	B	E	E	E	A	A	A	E	E	E	E
Solar and geothermal heating			E	E	A	D	E	E	B	A	E	A	A	E	E	E	E	A	A	A	A	A	E
Nuclear process heat			E	E	E	D	E	E	E	E	E	A	A	E	E	E	E	A	A	E	E	C	E
Other Processes:																							
Fuel switching and replacing fossil fuels by electricity in end-use sectors (partially a demand-side measure)			A	A	C	D	A	A	B	A	A	A	A	C	C	A	C	A	A	A	A	A	A
Substitution of halocarbons for refrigerants and insulation			C	E	E	D	E	C	C	E	E	E	E	E	E	A	E	A	A	A	D	E	C
Reduced gas flaring and leakage in extractive industries			C	E	A	D	D	C	C	E	E	E	A	E	E	C	E	B	B	A	C	D	D
Electrical transmission efficiency improvements, including smartgrids			B	E	C	D	A	E	E	E	E	B	B	E	E	B	C	E	E	E	E	B	E
Grid integration of intermittent renewables			E	E	C	D	A	C	E	C	D	A	A	E	E	C	C	C	C	A	A	D	C
Electricity storage			E	E	A	D	A	C	E	A	E	A	C	E	E	C	C	A	A	A	A	E	C
AFOLU Measures																							
Reduced deforestation, forest protection, avoided forest conversion			A	E	A	D	B	A	E	E	B	D	D	E	B	B	E	A	A	B	A	D	C
Forest management			C	E	E	D	E	C	E	E	C	D	D	E	B	B	E	A	A	B	E	D	C
Reduced land degradation, and forest restoration			C	E	D	D	E	E	E	E	C	D	D	E	E	B	E	E	E	B	E	D	E
Agroforestry and silviculture			E	E	D	D	E	E	E	E	E	D	D	E	E	E	E	E	E	E	E	E	E
Urban and peri-urban agriculture and forestry			E	E	E	D	E	E	E	E	E	D	D	E	E	E	E	E	E	E	E	E	E
Fire management and (ecological) pest control			C	E	D	D	E	C	E	E	E	D	D	E	E	E	E	E	E	E	E	E	E
Changing agricultural practices that enhance soil carbon			C	E	E	D	E	E	E	E	E	D	D	E	E	E	E	E	E	B	E	D	E
Conservation agriculture			E	E	E	D	E	E	E	E	E	D	D	E	E	E	E	A	A	E	E	E	C
Increasing agricultural productivity			A	E	A	D	A	B	E	E	B	D	D	E	A	B	E	A	A	E	A	D	C
Methane reductions in rice paddies			C	E	C	D	C	C	C	E	C	D	D	E	C	C	E	A	A	B	C	D	C
Nitrogen pollution reductions (e.g., by fertilizer reduction, increasing nitrogen fertilizer efficiency, sustainable fertilizers)			C	E	C	D	C	C	C	E	E	D	D	E	A	C	E	A	A	B	C	D	C
Livestock and grazing management, for example, methane and ammonia reductions in ruminants through feeding management or feed additives, or manure management for local biogas production to replace traditional biomass use			C	E	C	D	C	C	C	E	C	D	D	E	A	C	E	A	A	B	C	D	C
Manure management			C	E	C	D	C	C	C	E	C	D	D	E	C	C	E	A	A	E	C	E	C
Influence on land albedo of land use change			E	E	E	D	E	E	E	E	E	D	D	E	E	E	E	E	E	E	D	D	E

2SM

Table 2.SM.6 (continued)

Levels of Inclusion

	Explicit	Implicit
Endogenous	A	C
Exogenous	B	D
E	Not represented by model	

Carbon Dioxide (Greenhouse Gas) Removal	AIM	BET	COPPE-COFFEE	C-ROADS	DNE21+	GCAM 4.2	GEM-E3 3.0	GENESYSmod 1.0	GRAPE 1.0	IEA ETP	IEA WEM	IMACLIM 1.1	IMACLIM NL	IMAGE 3.0	MERGE-ETL 6.0	MESSAGE-GLOBIOM	MESSAGEix-GLOBIOM	POLES	REMIND-MAgPIE	Shell WEM v1	WITCH
Biomass use for energy production with carbon capture and sequestration (BECCS) (through combustion, gasification, or fermentation)	A	A	A	D	A	A	E	E	A	A	A	A	A	A	A	A	E	A	A	B	A
Direct air capture and sequestration (DACS) of CO_2 using chemical solvents and solid absorbents, with subsequent storage	E	E	E	D	E	E	E	E	E	E	E	E	E	E	A	E	E	E	A	E	E
Mineralization of atmospheric CO_2 through enhanced weathering of rocks	E	E	E	D	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E
Afforestation/Reforestation	A	E	A	C	A	A	E	E	A	E	E	E	B	B	E	A	A	B	A	D	A
Restoration of wetlands (e.g., coastal and peat-land restoration, blue carbon)	E	E	E	D	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E
Biochar	E	E	E	D	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E
Soil carbon enhancement, enhancing carbon sequestration in biota and soils, e.g. with plants with high carbon sequestration potential (also AFOLU measure)	E	E	E	D	E	E	E	E	E	E	E	E	D	E	E	A	A	B	C	E	E
Carbon capture and usage (CCU); bioplastics (bio-based materials replacing fossil fuel uses as feedstock in the production of chemicals and polymers), carbon fibre	E	E	E	D	E	C	E	E	E	A	B	E	E	A	E	E	E	E	E	A	E
Material substitution of fossil CO_2 with bio-CO_2 in industrial application (e.g. the beverage industry)	E	E	E	D	E	C	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E
Ocean iron fertilization	E	E	E	D	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E
Ocean alcanization	E	E	E	D	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E
Removing CH_4, N_2O and halocarbons via photocatalysis from the atmosphere	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E

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 facilitates determining 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 shared policy assumptions (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. The SSP3-SPA3 scenario for 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 have been selected for representing a specific SSP particularly adequately, and are indicated in blue. Source: Rogelj et al., 2018.

Model	Methodology	Reported scenario				
		SSP1-SPA1	SSP2-SPA2	SSP3-SPA3	SSP4-SPA4	SSP5-SPA5
AIM	General equilibrium (GE)	1	1	0*	0	0
GCAM4	Partial equilibrium (PE)	1	1	X	0	1
IMAGE	Hybrid (system dynamic models and GE for agriculture)	1	0	0*	X	X
MESSAGE-GLOBIOM	Hybrid (systems engineering PE model)	1	1	0*	X	X
REMIND-MAgPIE	General equilibrium (GE)	1	1	X	X	1
WITCH-GLOBIOM	General equilibrium (GE)	1	0	0	1	0

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 https://data.ene.iiasa.ac.at/iamc-1.5c-explorer/. 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 will also be 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 Nationally Determined Contribution (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 be integrated into the assessment to a very limited degree, as they lacked the longer-term perspective. 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 by 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 $GtCO_2e\ yr^{-1}$ using the GWP_{100} metric from the IPCC Second Assessment Report (SAR). 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 by 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 zero or missing values in at least one year. These scenarios were excluded from the analysis in Section 2.5 and Figure 2.26 in Chapter 2.

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/REMIND–MAgPIE	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
	Multimodel 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.	Vrontisi et al. (2018)	9 (6)	74	55
	Decarbonization 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.	Luderer et al. (2018)			
CD-LINKS	Exploring interactions between climate and sustainable development policies, with the aim to identify robust integral policy packages to achieve all objectives.	McCollum et al. (2018)	8 (6)	36	36
	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.				
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

Table 2.SM.9 (continued)

Study/Model Name	Key Focus	Reference Papers	Modelling Frameworks	Scenarios Submitted	Scenarios Assessed
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 (REMIND)	Exploring how delay closes the door to achieve various temperature targets, including limiting warming to 1.5°C	Luderer et al. (2013)		8	8
MESSAGE GEA	Exploring the relative importance of technological, societal, geophysical and political uncertainties for limiting warming to 1.5°C and 2°C.	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°C) ≤ 0.34	0
	Below 1.5°C	Below-1.5°C	0.34 < P(1.5°C) ≤ 0.5	9
	1.5°C Return with low overshoot (OS)	1.5°C-low-OS	0.5 < P(1.5°C) ≤ 0.67 AND P(1.5°C in 2100) ≤ 0.34	34
			0.5 < P(1.5°C) ≤ 0.67 AND 0.34 < P(1.5°C in 2100) ≤ 0.5	10
	1.5°C Return with high OS	1.5°C-high-OS	0.67 < P(1.5°C) AND P(1.5°C in 2100) ≤ 0.34	19
			0.67 < P(1.5°C) AND 0.34 < P(1.5°C in 2100) ≤ 0.5	18
2°C	Lower 2°C	Lower-2°C	P(2°C) ≤ 0.34 (excluding above)	74
	Higher 2°C	Higher-2°C	0.34 < P(2°C) ≤ 0.5 (excluding above)	58
Above 2°C	Above 2°C	-	0.5 < P(2°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 Chapter 2, 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).

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 between 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 5.2 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 5.2, 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 5.2, the main interaction (synergies, synergy or trade-off, trade-off) is based on all interactions with three-star (★★★) and four-star (★★★★) confidence ratings in Table 5.2. If no three-star or four-star 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 three-star 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 three-star and four-star 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; four-star confidence in Table 5.2 is also reported as three-star in the Chapter 2 synthesis)
- If a measure in Table 5.2 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

Table 2.SM.12 | Geophysical characteristics of mitigation pathways derived at median peak temperature and at the end of the century (2100). Overshoot severity is the sum of median degree warming years exceeding 1.5°C over the 21st century. NA indicates that no mitigation pathways exhibit the given geophysical characteristic. Radiative forcing metrics are: total anthropogenic radiative forcing (RF all), CO_2 radiative forcing (RF CO_2), and non-CO_2 radiative forcing (RF non CO_2). Cumulative CO_2 emissions until peak median warming or 2100 are given for submitted and harmonized IAM outputs and are rounded at the nearest 10 $GtCO_2$. Values show: median (25th to 75th percentile) across scenarios. 'NoR' indicates that median warming exceeds 1.5°C but never returns below it before 2100. Scenarios with year-2010 Kyoto-GHG emissions outside the range assessed by IPCC AR5 Working Group III are excluded, as are scenario duplicates that would bias ranges towards a single study.
[*]: this statistic is computed from the three scenarios where median warming exceeds 2°C and returns below 2°C before 2100.

			Geophysical Characteristics at Peak Warming											Geophysical Characteristics in 2100									Geophysical Characteristics of the Temperature Overshoot				
Category	**# scenarios with climate assessment**	**Peak|Median warming**	**Peak|Year**	**Peak|CO_2 [ppm]**	**Peak|RF all [W m⁻²]**	**Peak|RF CO_2 [W m⁻²]**	**Peak|RF non CO_2 [W m⁻²]**	**Net zero CO_2 |Year**	**Cumulative CO_2 emissions (2016 to peak warming) as submitted [$GtCO_2$]**	**Cumulative CO_2 emissions (2016 to peak warming) harmonized [$GtCO_2$]**	**Peak|Exeedance Probability 1.5°C [%]**	**Peak|Exeedance Probability 2.0°C [%]**	**Peak|Exeedance Probability 2.5°C [%]**	**2100| CO_2 [ppm]**	**2100|RF all [W m⁻²]**	**2100|RF CO_2 [W m⁻²]**	**2100|RF non-CO_2 [W m⁻²]**	**Cumulative CO_2 emissions (2016-2100) as submitted [$GtCO_2$]**	**Cumulative CO_2 emissions (2016-2100) harmonized [$GtCO_2$]**	**2100|Exeedance Probability 1.5°C [%]**	**2100|Exeedance Probability 2.0°C [%]**	**2100|Exeedance Probability 2.5°C [%]**	**Exceedance year|1.5°C [year]**	**Overshoot duration|1.5°C [number of years]**	**Overshoot severity|1.5°C [temperature-years]**	**Exceedance year|2.0°C [year]**	**Overshoot duration|2.0°C [number of years]**
Below-1.5°C	5	1.5 (1.5, 1.5)	2041 (2040, 2046)	423 (422, 424)	2.9 (2.8, 2.9)	2.3 (2.3, 2.3)	0.6 (0.6, 0.6)	2044 (2038, 2050)	480 (480, 490)	460 (460, 470)	45 (42, 46)	5 (5, 5)	1 (1, 1)	376 (374, 378)	1.8 (1.8, 2.0)	1.6 (1.6, 1.7)	0.3 (0.2, 0.3)	180 (180, 180)	150 (150, 220)	16 (14, 19)	3 (3, 4)	1 (1, 1)	NA	NA	NA	NA	NA
1.5°C-low-OS	37	1.6 (1.5, 1.6)	2048 (2045, 2050)	431 (429, 435)	3.0 (2.9, 3.0)	2.4 (2.3, 2.4)	0.6 (0.5, 0.6)	2050 (2047, 2055)	620 (600, 670)	620 (590, 670)	60 (56, 62)	10 (9, 12)	1 (1, 2)	380 (376, 387)	2.1 (2.0, 2.2)	1.7 (1.6, 1.8)	0.3 (0.3, 0.4)	260 (180, 360)	270 (140, 340)	28 (25, 32)	7 (6, 8)	1 (1, 2)	2035 (2033, 2036)	27 (21, 37)	1 (1, 2)	NA	NA
1.5°C-high-OS	36	1.7 (1.6, 1.7)	2051 (2048, 2053)	447 (440, 454)	3.2 (3.1, 3.3)	2.6 (2.5, 2.7)	0.6 (0.6, 0.7)	2052 (2049, 2059)	840 (760, 930)	870 (760, 930)	75 (72, 78)	18 (14, 20)	3 (2, 4)	385 (374, 405)	2.2 (2.0, 2.4)	1.8 (1.6, 2.0)	0.4 (0.3, 0.5)	330 (190, 630)	360 (180, 620)	33 (30, 45)	8 (8, 12)	2 (1, 3)	2033 (2032, 2033)	52 (43, 60)	6 (4, 8)	NA	NA
Lower-2°C	54	1.7 (1.7, 1.8)	2061 (2059, 2074)	454 (446, 458)	3.2 (3.1, 3.3)	2.6 (2.5, 2.7)	0.6 (0.5, 0.7)	2070 (2063, 2079)	990 (890, 1080)	1000 (900, 1070)	79 (75, 82)	26 (22, 28)	6 (6, 7)	425 (419, 436)	2.8 (2.6, 2.9)	2.3 (2.2, 2.4)	0.4 (0.4, 0.5)	840 (780, 970)	860 (770, 970)	66 (59, 72)	21 (17, 26)	7 (6, 9)	2033 (2032, 2034)	NoR	NoR	NA	NA
Higher-2°C	54	1.9 (1.9, 2.0)	2078 (2069, 2100)	473 (464, 478)	3.4 (3.3, 3.5)	2.8 (2.8, 2.9)	0.5 (0.5, 0.7)	2084 (2070, post-2100)	1320 (1170, 1450)	1320 (1150, 1490)	87 (85, 89)	40 (38, 46)	13 (11, 15)	451 (435, 471)	3.1 (2.9, 3.3)	2.6 (2.4, 2.8)	0.5 (0.4, 0.5)	1260 (1000, 1450)	1260 (1000, 1470)	83 (76, 86)	38 (31, 43)	13 (10, 15)	2033 (2032, 2034)	NoR	NoR	NA	NA
Above-2°C	182	3.1 (2.2, 3.8)	Post-2100	651 (520, 777)	5.4 (3.9, 6.6)	4.6 (3.4, 5.5)	0.8 (0.6, 1.2)	post-2100	3550 (2000, 4790)	3530 (1980, 4780)	100 (95, 100)	96 (69, 100)	84 (31, 97)	651 (510, 777)	5.4 (3.8, 6.6)	4.6 (3.2, 5.5)	0.8 (0.5, 1.2)	3550 (1980, 4790)	3530 (1970, 4780)	100 (95, 100)	96 (68, 100)	84 (30, 97)	2032 (2031, 2033)	NoR	NoR	2051 (2047, 2058)	35 (26, 37) [*]

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 indicator 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 summing 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 5.2 of Chapter 5 to the condensed set of mitigation measured used for the mitigation-SDG synthesis of Chapter 2.

Table 5.2 Mitigation Measures Set			Chapter 2 Condensed Set
Demand	Industry	Accelerating energy efficiency improvement	DEMAND: Accelerating energy efficiency improvements in end use sectors
		Low-carbon fuel switch	DEMAND: Fuel switch and access to modern low-carbon energy
		Decarbonization/CCS/CCU	Not included
	Buildings	Behavioural response	DEMAND: Behavioural response reducing Building and Transport demand
		Accelerating energy efficiency improvement	DEMAND: Accelerating energy efficiency improvements in end use sectors
		Improved access & fuel switch to modern low-carbon energy	DEMAND: Fuel switch and access to modern low-carbon energy
	Transport	Behavioural response	DEMAND: Behavioural response reducing Building and Transport demand
		Accelerating energy efficiency improvement	DEMAND: Accelerating energy efficiency improvements in end use sectors
		Improved access & fuel switch to modern low-carbon energy	DEMAND: Fuel switch and access to modern low-carbon energy
Supply	Replacing coal	Non-biomass renewables: solar, wind, hydro	SUPPLY: Non-biomass renewables: solar, wind, hydro
		Increased use of biomass	SUPPLY: Increased use of biomass
		Nuclear/advanced nuclear	SUPPLY: Nuclear/advanced nuclear
		CCS: Bio energy	SUPPLY: Bioenergy with carbon capture and storage (BECCS)
	Advanced coal	CCS: Fossil	SUPPLY: Fossil fuels with carbon capture and storage (fossil-CCS)
Land & Ocean	Agriculture & Livestock	Behavioural response: Sustainable healthy diets and reduced food waste	DEMAND: Behavioural response: Sustainable healthy diets and reduced food waste
		Land based greenhouse gas reduction and soil carbon sequestration	LAND: Land-based greenhouse gas reduction and soil carbon sequestration
		Greenhouse gas reduction from improved livestock production and manure management systems	LAND: Greenhouse gas reduction from improved livestock production and manure management systems
	Forest	Reduced deforestation, REDD+	LAND: Reduced deforestation, REDD+, afforestation and reforestation
		Afforestation and reforestation	LAND: Reduced deforestation, REDD+, afforestation and reforestation
		Behavioural response (responsible sourcing)	Not included
	Oceans	Ocean iron fertilization	Not included
		Blue carbon	Not included
		Enhanced Weathering	Not included

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 inversely related with the deployment of the respective measures.

Mitigation Measure		Pathway Proxy	
Group	**Description**	**Code**	**Description**
Demand	Accelerating energy efficiency improvements in end-use sectors	1	Compound annual growth rate of primary energy (PE) to final energy (FE) conversion from 2020 to 2050
	Behavioural response reducing Building and Transport demand	2	Percent change in FE between 2010 and 2050
	Fuel switch and access to modern low-carbon energy	3	Year-2050 carbon intensity of FE
	Behavioural response: Sustainable healthy diets and reduced food waste	4	Year-2050 share of non-livestock in food energy supply
Supply	Non-biomass renewables: solar, wind, hydro	5	Year-2050 PE from non-biomass renewables
	Increased use of biomass	6	Year-2050 PE from biomass
	Nuclear/advanced nuclear	7	Year-2050 PE from nuclear
	Bioenergy with carbon capture and storage (BECCS)	8	Year-2050 BECCS deployment in $GtCO_2$
	Fossil fuels with carbon capture and storage (fossil-CCS)	9	Year-2050 fossil-CCS deployment in $GtCO_2$
Land	Land based greenhouse gas reduction and soil carbon sequestration	10	Cumulative AFOLU CO_2 emissions over the 2020–2100 period
	Greenhouse gas reduction from improved livestock production and manure management systems	11	CH_4 and N_2O AFOLU emissions per unit of total food energy supply
	Reduced deforestation, REDD+, afforestation and reforestation	12	Change in global forest area between 2020 and 2050

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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 are drawn from the ADVANCE IAM wiki documentation, available at www.iamcdocumentation.eu (last accessed on 15 May 2018) 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
AIM/CGE

Institution and users
National Institute for Environmental Studies (NIES), Japan

Model scope and methods

Objective
AIM/CGE is developed to analyse climate mitigation and impacts. The energy system is disaggregated to meet this objective on both the energy supply and demand sides. Agricultural sectors have also been disaggregated for the appropriate land-use treatment. The model is designed to be flexible in its use for global analysis.

Concept
General equilibrium with technology-explicit modules in power sectors

Solution method
Solving a mixed complementarity problem

Anticipation
Myopic

Temporal dimension
Base year: 2005
Time steps: Annual
Horizon: 2100

Spatial dimension
Number of regions: 17
Japan, China, India, Southeast Asia, Rest of Asia, Oceania, EU25, Rest of Europe, Former Soviet Union, Turkey, Canada, United States, Brazil, Rest of South America, Middle East, North Africa, Rest of Africa

Policy implementation
Climate policies such as emissions targets, emission permit trading and so on. Energy taxes and subsidies

Socio-economic drivers

Exogenous drivers
Total factor productivity
Note: GDP is endogenous, while TFP is exogenous; but TFP can be calibrated so as to reproduce a given GDP pathway

Endogenous drivers
GDP (Non-baseline scenarios that take into account either climate change mitigation or impacts.)

Development
GDP per capita

Macro economy

Economic sectors
Agriculture, industry, energy, transport, services

Cost measures
GDP loss, welfare loss, consumption loss

Trade
Coal, oil, gas, electricity, food crops, emissions permits, non-energy goods

Energy

Behaviour
None

Resource use
Coal, oil, gas, biomass

Electricity technologies
Coal, gas, oil, nuclear, biomass, wind, solar PV, CCS

Conversion technologies
Oil to liquids, biomass to liquids

Grid and infrastructure
None

Energy technology substitution
Discrete technology choices

Energy service sectors
Transportation, industry, residential and commercial

Land use

Land cover
Abandoned land, cropland, forest, grassland, extensive pastures
note: 6 AEZs (agro-ecological zones) by crop, pasture, forestry, other forest, natural grassland and others. There is a land competition under multinomial logit selection.

Other resources

None

Emissions and climate

Greenhouse gases
CO_2, CH_4, N_2O, HFCs, CFCs, SF_6

Pollutants
NO_x, SO_x, BC, OC, VOC, CO

Climate indicators
CO_2e concentration (ppm), radiative forcing (W m^{-2}), temperature change (°C)

2.SM.2.2 Reference Card – BET

About

Name and version

BET EMF33

Institution and users

CRIEPI, University of Tokyo, *Role of end-use technologies in long-term GHG reduction scenarios developed with the BET model* doi: 10.1007/s10584-013-0938-6

Model scope and methods

Objective

The model is used for climate change studies on long-term mitigation scenarios. Typical application is to examine the role of electrification and advanced end-use technologies in climate change mitigation in a more systematic fashion, ranging from changes in usage of end-use technologies to power generation mix.

Concept

General equilibrium (closed economy)

Solution method

Optimization

Anticipation

Inter-temporal (foresight)

Temporal dimension

Base year: 2010

Time steps: 10

Horizon: 2010–2230

Spatial dimension

Number of regions: 13

BRA (Brazil), CAZ (Canada, Australia, and New Zealand), CHA (China incl. Hong Kong), EUR (EU27 + Switzerland, Norway, and Iceland), IND (India), JPN (Japan), MNA (Middle East and North Africa), OAS (Other Asia), OLA (Other Latin America), ORF (Other Reforming Economies), RUS (Russia), SSA (Sub-Saharan Africa), USA (United States)

Policy implementation

Emission tax/pricing, cap and trade

Socio-economic drivers

Exogenous drivers

Population, total factor productivity, autonomous energy efficiency improvements

Endogenous drivers

GDP, end-use service demand

Macro economy

Economic sectors

Aggregated representation (single-sector economy)

Cost measures

GDP loss, consumption loss, energy system costs

Trade

Coal, oil, gas, hydrogen, food crops (exogenous), emissions permits, non-energy goods

Energy

Behaviour

None

Resource use

Coal, conventional oil, unconventional oil, conventional gas, unconventional gas, uranium, bioenergy

Electricity technologies

Coal w/o CCS, coal w/ CCS, gas w/o CCS, gas w/ CCS, oil w/o CCS, bioenergy w/o CCS, bioenergy w/ CCS, geothermal power, nuclear power, solar power (central PV), wind power (onshore), wind power (offshore), hydroelectric power, hydrogen fuel

Conversion technologies

Coal to hydrogen w/ CCS, electrolysis, coal to liquids w/o CCS, bioliquids w/o CCS, oil refining, biomass to gas w/o CCS

Grid and infrastructure

Electricity

Note: Generalized transmission and distribution costs are included, but not modelled in a spatially explicit manner.

Gas

Note: Generalized gas network costs are included, but not modelled in a spatially explicit manner.

Energy technology substitution

Linear choice (lowest cost, only for the supply side), expansion and decline constraints, system integration constraints

Energy service sectors

Transportation, industry, residential and commercial

Land use

Land cover

Cropland food crops, cropland feed crops, cropland energy crops, managed forest, natural forest, pasture

Other resources

None

Emissions and climate

Greenhouse gases

CO_2

Pollutants

None

Climate indicators

CO_2 concentration (ppm), radiative forcing (W m^{-2})

2.SM.2.3 Reference Card – C-ROADS

About

Name and version

C-ROADS v5.005

Institution and users

Climate Interactive, US, https://www.climateinteractive.org/.

Model scope and methods

Objective

The purpose of C-ROADS is to improve public and decision-maker understanding of the long-term implications of international emissions and sequestration futures with a rapid-iteration, interactive tool as a path to effective action that stabilizes the climate.

Concept

C-ROADS takes future population, economic growth and GHG emissions as scenario inputs specified by the user and currently omits the costs of policy options and climate change damage.

Solution method

Recursive dynamic solution method (myopic)

Anticipation

Simulation modelling framework, without foresight.

Temporal dimension

Base year: 1850

Time steps: 0.25 year time step

Horizon: 2100

Spatial dimension

Number of regions: 20

USA ,European Union (EU) 27 (EU27) (plus Iceland, Norway and Switzerland), Russia (includes fraction of former USSR), other Eastern Europe, Canada, Japan, Australia, New Zealand, South Korea, Mexico, China, India, Indonesia, Philippines, Thailand, Taiwan, Hong Kong, Malaysia, Pakistan, Singapore, Brazil, Latin America excluding Mexico and Brazil, Middle East, South Africa, Africa excluding South Africa, Asia excluding China, India, Indonesia, and those included in Other Large Asia

Policy implementation

The model includes implicit representation of policies. For each well-mixed GHG, regionally specified socio-economic drivers, emissions per GDP, and emissions changes relative to a reference year or reference scenario determine emissions pathways.

Socioeconomic drivers

Exogenous drivers

Exogenous population, exogenous GDP per capita rates and convergence times are used to model GDP over time.

Endogenous drivers

None

Development

None

Macro economy

Economic sectors

Not represented by the model

Cost measures

Not represented by the model

Trade

Not represented by the model

Energy

Behaviour

Not represented by the model

Resource use

Not represented by the model

Electricity technologies

Not represented by the model

Conversion technologies

Not represented by the model

Grid and infrastructure

Not represented by the model

Energy technology substitution

Not represented by the model

Energy service sectors

Not represented by the model

Land use

Land cover

Not represented by the model

Other resources

None

Emissions and climate

Greenhouse gases

CO_2, CH_4, N_2O, HFCs, CFCs, SF_6, PFCs

Pollutants

Not modelled. Covered by the model in terms of radiative forcing; uses projections of a specified SSP scenario

Climate indicators

The cycle of each well-mixed greenhouse gas is explicitly modelled. CO_2 concentration (ppm), CH_4 concentration (ppb), N_2O concentration (ppb), HFCs concentration (ppt), SF_6 concentration (ppt), PFCs concentration (ppt), CO_2e concentration (ppm), radiative forcing (W m^{-2})

The model uses the radiative efficiencies and explicitly-modelled concentration over time of each well-mixed greenhouse to determine its radiative forcing (RF). The model also uses a specified SSP scenario for exogenous values of other forcings, which includes those from aerosols, albedo, solar irradiance and volcanic activity. The total RF is the sum of these components.
Temperature change (°C), sea level rise, ocean acidification.

2.SM.2.4 Reference Card – DNE21+

About

Name and version
DNE21+ V.14C

Institution and users
Research Institute of Innovative Technology for the Earth (RITE), 9-2 Kizugawadai, Kizugawa-shi, Kyoto 619-0292
http://www.rite.or.jp/Japanese/labo/sysken/about-global-warming/download-data/RITE_GHGMitigationAssessmentModel_20150130.pdf
https://www.rite.or.jp/system/en/research/new-earth/dne21-model-analyses/climate/

Model scope and methods

Objective
None

Concept
Minimizing energy systems cost

Solution method
Optimization

Anticipation
Inter-temporal (foresight)

Temporal dimension
Base year: 2000
Time steps: 5 year steps (2000 - 2030); 10 year-steps (2030 - 2050)
Horizon: 2000-2050

Spatial dimension
Number of regions: 54
ARG+ (Argentina, Paraguay, Uruguay), AUS (Australia), BRA (Brazil), CAN (Canada), CHN (China), EU15 (EU-15), EEU (Eastern Europe – Other EU-28), IND (India), IDN (Indonesia), JPN (Japan), MEX (Mexico), RUS (Russia), SAU (Saudi Arabia), SAF (South Africa), ROK (South Korea), TUR (Turkey), USA (United States of America), OAFR (Other Africa), MEA (Middle East & North Africa), NZL (New Zealand), OAS (Other Asia), OFUE (Other FUSSR – Eastern Europe), OFUA (Other FUSSR – Asia), OLA (Other Latin America), OWE (Other Western Europe)

Policy implementation
Emission tax/pricing, cap and trade, fuel taxes, fuel subsidies, feed-in-tariff, portfolio standard, capacity targets, emission standards, energy efficiency standards, land protection, pricing carbon stocks

Socio-economic drivers

Exogenous drivers
Population, population age structure, education level, urbanization rate, GDP, income distribution, labour participation rate, labour productivity

Macro economy

Economic sectors
Agriculture, industry, energy, services

Cost measures
Energy system costs

Trade
Coal, oil, gas, electricity, emissions permits

Energy

Behaviour
Transportation, industry, residential & commercial, technology adoption

Resource use
Coal, conventional oil, unconventional oil, conventional gas, unconventional gas

Electricity technologies
Coal w/o CCS, coal w/ CCS, gas w/o CCS, gas w/ CCS, oil w/o CCS, oil w/ CCS, bioenergy w/o CCS, bioenergy w/ CCS, geothermal power, nuclear power, solar power, wind power, hydroelectric power

Conversion technologies
Coal to hydrogen w/o CCS, coal to hydrogen w/ CCS, natural gas to hydrogen w/o CCS, natural gas to hydrogen w/ CCS, biomass to hydrogen w/o CCS, biomass to hydrogen w/ CCS, electrolysis, coal to liquids w/o CCS, bioliquids w/o CCS, oil refining, coal to gas w/o CCS

Grid and infrastructure
Electricity, gas, CO_2, H_2

Energy technology substitution
Linear choice (lowest cost), system integration constraints

Energy service sectors
Transportation, industry, residential and commercial

Land use

Land cover
Cropland food crops, cropland feed crops, cropland energy crops, managed forest, natural forest, pasture

Other resources

Other resources
Water

Emissions and climate

Greenhouse gases
CO_2, CH_4, N_2O, HFCs, CFCs, SF_6

Pollutants
NO_X, SO_X, BC, OC

Climate indicators
CO_2e concentration (ppm), radiative forcing (W m^{-2}), temperature change (°C)

2.SM.2.5 Reference Card – FARM 3.2

About

Name and version
Future Agricultural Resources Model 3.2

Institution and users
United States Department of Agriculture, Economic Research Service; Öko-Institut, Germany https://www.ers.usda.gov/webdocs/publications/81903/err-223.pdf?v=42738

Model scope and methods

Objective
The Future Agricultural Resources Model (FARM) was originally designed as a static computable general equilibrium (CGE) model to simulate land use and climate impacts at a global scale. It has since been extended to simulate energy and agricultural systems through 2100 to enable participation in the energy modelling forum (EMF) and the agricultural modelling intercomparison project (AgMIP) model comparison studies.

Concept
FARM models land-use shifts among crops, pasture, and forests in response to population growth; changes in agricultural productivity; and policies such as a renewable portfolio standard or greenhouse gas cap-and-trade.

Solution method
General equilibrium recursive-dynamic simulation

Anticipation
Myopic

Temporal dimension
Base year: 2011
Time steps: 5 years
Horizon: 2101

Spatial dimension
Number of regions: 15
United States, Japan, European Union west (EU-15), European Union east, Other OECD90, Russian Federation, Other Reforming Economies China region, India, Indonesia, Other Asia, Middle East and North Africa, Sub-Saharan Africa, Brazil, Other Latin America

Policy implementation
Emissions tax/pricing, cap and trade, fuel taxes and subsidies, portfolio standards, agricultural producer, subsidies, agricultural consumer subsidies, land protection

Socio economic drivers

Exogenous drivers
Population, labour productivity, land productivity, autonomous energy efficiency improvements, other input-specific productivity

Endogenous drivers
None

Development
None

Macro economy
Economic sectors
Agriculture, industry, energy, services

Cost measures
GDP loss, welfare loss, equivalent variation, consumption loss

Trade
Coal, oil, gas, electricity, food crops, non-energy goods

Energy
Behaviour
Substitution between energy and non-energy inputs in response to changes in relative prices

Resource use
Coal (supply curve), conventional oil (supply curve), conventional gas (supply curve), biomass (supply curve)

Electricity technologies
Coal (w/o and w/ CCS), gas (w/o and w/ CCS), oil (w/o and w/ CCS), nuclear, biomass (w/o and w/ CCS), wind, solar PV

Conversion technologies
Fuel to liquid, oil refining

Grid and infrastructure
Electricity (aggregate), gas (aggregate), CO_2 (aggregate)

Energy technology substitution
Discrete technology choices with mostly high substitutability through production functions

Energy service sectors
Transportation (land, water, air), buildings

Land use
Land cover
Crop land, food crops, feed crops, energy crops, managed forest, pastures

Other resources
Other resources
None

Emissions and climate
Greenhouse gases
CO_2, fossil fuels, cement, land use

Pollutants
None

Climate indicators
None

2.SM.2.6 Reference Card – GCAM 4.2

About
Name and version
Global Change Assessment Model 4.2

Institution and users
Joint Global Change Research Institute – http://jgcri.github.io/gcam-doc/v4.2/toc.html

Model scope and methods
Objective
GCAM is a global integrated assessment model that represents the behaviour of, and complex interactions between five systems: the energy system, water, agriculture and land use, the economy, and the climate.

Concept
The core operating principle for GCAM is that of market equilibrium. Representative agents in GCAM use information on prices, as well as other information that might be relevant, and make decisions about the allocation of resources. These representative agents exist throughout the model, representing, for example, regional electricity sectors, regional refining sectors, regional energy demand sectors, and land users who have to allocate land among competing crops within any given land region. Markets are the means by which these representative agents interact with one another. Agents pass goods and services along with prices into the markets. Markets exist for physical flows such as electricity or agricultural commodities, but they also can exist for other types of goods and services, for example tradable carbon permits.

Solution method
Partial equilibrium (price elastic demand) recursive-dynamic

Anticipation
Myopic

Temporal dimension
Base year: 2010
Time steps: 5 years
Horizon: 2100

Spatial dimension
Number of regions: 32 (For CD-Links scenarios, GCAM included 82 regions)
USA (For CD-Links scenarios, the USA was subdivided into 50 states plus the District of Columbia), Eastern Africa, Northern Africa, Southern Africa, Western Africa, Australia and New Zealand, Brazil, Canada, Central America and Caribbean, Central Asia, China, EU-12, EU-15, Eastern Europe, Non-EU Europe, European Free Trade Association, India, Indonesia, Japan, Mexico, Middle East, Pakistan, Russia, South Africa, Northern South America, Southern South America, South Asia, South Korea, Southeast Asia, Taiwan, Argentina, Colombia

Policy implementation
Climate policies, Emission tax/pricing, cap and trade, energy policies,

fuel taxes, fuel subsidies, portfolio standard, energy technology policies, capacity targets, energy efficiency standards, land-use policies, land protection, afforestation

Socio-economic drivers

Exogenous drivers

Population, GDP, labour participation rate, labour productivity

Endogenous drivers

None

Development

None

Macro economy

Economic sectors

Agriculture, industry, energy, transport, services, residential and commercial

Cost measures

Area under marginal abatement cost (MAC) curve

Trade

Coal, oil, gas, uranium, bioenergy crops, food crops, emissions permits

Energy

Behaviour

None

Resource use

Coal (supply curve), conventional oil (supply curve), unconventional oil (supply curve), conventional gas (supply curve), unconventional gas (supply curve), uranium (supply curve), biomass (process model), land

Electricity technologies

Coal (w/ o and w/ CCS), gas (w/o and w/ CCS), oil (w/o and w/ CCS), nuclear, biomass (w/o and w/ CCS), wind (onshore), solar PV (central PV, distributed PV, and concentrating solar power), CCS

Conversion technologies

CHP, hydrogen from coal, oil, gas, and biomass, w/o and w/ CCS, nuclear and solar thermochemical, fuel to gas, coal to gas w/o CCS, biomass (w/o and w/ CCS), fuel to liquid, coal to liquids (w/o and w/ CCS), gas to liquids (w/o and w/ CCS), biomass to liquids (w/o and w/ CCS)

Grid and infrastructure

None

Energy technology substitution

Discrete technology choices with usually high substitutability through logit-choice model

Energy service sectors

Transportation, residential and commercial, industry

Land use

Land cover

Cropland, food crops, feed crops, energy crops, forest, managed forest, natural forest, pasture, shrubland, tundra, urban, rock, ice, desert

Other resources

Other resources

Water, cement

Emissions and climate

Greenhouse gases

CO_2 (fossil fuels, cement, land use), CH_4 (energy, land use, other), N_2O (energy, land use, other), HFCs, CFCs, SF_6

Pollutants

NO_X (energy, land use), SO_X (energy, land use), BC (energy, land use), OC (energy, land use), NH_3 (energy, land use)

Climate indicators

Kyoto-gases concentration, radiative forcing (W m^{-2}), temperature change (°C)

2.SM.2.7 Reference Card – GEM-E3

About

Name and version

GEM-E3

Institution and users

Institute of Communication and Computer Systems (ICCS), Greece
https://ec.europa.eu/jrc/en/gem-e3

Model scope and methods

Objective

The model puts emphasis on: (i) the analysis of market instruments for energy-related environmental policy, such as taxes, subsidies, regulations, emission permits etc., at a degree of detail that is sufficient for national, sectoral and world-wide policy evaluation; and (ii) the assessment of distributional consequences of programmes and policies, including social equity, employment and cohesion for less-developed regions.

Concept

General equilibrium

Solution method

The model is formulated as a simultaneous system of equations with an equal number of variables. The system is solved for each year following a time-forward path. The model uses the GAMS software and is written as a mixed non-linear complementarity problem solved by using the PATH algorithm with the standard solver options.

Anticipation

Myopic

Temporal dimension

Base year: 2011
Time steps: Five year time steps
Horizon: 2050

Spatial dimension

Different spatial dimension depending on application. Main applications feature one of the two regional disaggregation below.

Number of regions: 38
Austria, Belgium, Bulgaria, Croatia, Cyprus, Czech Republic, Germany, Denmark, Spain, Estonia, Finland, France, United Kingdom, Greece, Hungary, Ireland, Italy, Lithuania, Luxembourg, Latvia, Malta, Netherlands, Poland, Portugal, Slovakia, Slovenia, Sweden, Romania, USA, Japan, Canada, Brazil, China, India, Oceania, Russian federation, Rest of Annex I, Rest of the World

Or

Number of regions: 19
EU28, USA, Japan, Canada, Brazil, China, India, South Korea, Indonesia, Mexico, Argentina, Turkey, Saudi Arabia, Oceania, Russian federation, rest of energy producing countries, South Africa, rest of Europe, rest of the World

Policy implementation

Taxes, permits trading, subsidies, energy efficiency standards, CO_2 standards, emission-reduction targets, trade agreements, R&D, adaptation.

Socio-economic drivers

Exogenous drivers

Total factor productivity, labour productivity, capital technical progress, energy technical progress, materials technical progress, active population growth

Endogenous drivers

Learning-by-doing

Development

GDP per capita, labour participation rate

Macro economy

Economic sectors

Agriculture, industry, energy, transport, services, other

Note: GEM-E3 represents the following sectors: Agriculture, coal, crude oil, oil, gas, electricity supply, ferrous metals, non-ferrous metals, chemical products, paper & pulp, non-metallic minerals, electric goods, conventional transport equipment, other equipment goods, consumer goods industries, construction, air transport, land transport – passenger, land transport – freight, water transport – passenger, water transport – freight, biofuel feedstock, biomass, ethanol, biodiesel, advanced electric appliances, electric vehicles, equipment for wind, equipment for PV, equipment for CCS, market services, non-market services, coal fired, oil fired, gas fired, nuclear, biomass, hydroelectric, wind, PV, CCS coal, CCS gas

Cost measures

GDP loss, welfare loss, consumption loss

Trade

Coal, oil, gas, electricity, emissions permits, non-energy goods, agriculture, ferrous and non-ferrous metals, chemical products, other energy intensive, electric goods, transport equipment, other equipment goods, consumer goods industries

Energy

Behaviour

The GEM-E3 model endogenously computes energy consumption, depending on energy prices, realized energy efficiency expenditures and autonomous energy efficiency improvements. Each agent decides how much energy it will consume in order to optimize its behaviour (i.e., to maximize profits for firms and utility for households) subject to technological constraints (i.e., a production function). At a sectoral level, energy consumption is derived from profit maximization under a nested CES (constant elasticity of substitution) specification. Energy enters the production function together with other production factors (capital, labour, materials). Substitution of energy and the rest of the production factors is imperfect (energy is considered an essential input to the production process) and it is induced by changes in the relative prices of each input. Residential energy consumption is derived from the utility maximization problem of households. Households allocate their income between different consumption categories and savings to maximize their utility subject to their budget constraint. Consumption is split between durable (e.g., vehicles, electric appliances) and non-durable goods. For durable goods, stock accumulation depends on new purchases and scrapping.

Durable goods consume (non-durable) goods and services, including energy products. The latter are endogenously determined depending on the stock of durable goods and on relative energy prices.

Resource use
Coal, oil, gas, biomass

Electricity technologies
Coal, gas, oil, nuclear, biomass, wind, solar PV, ,CCS

Conversion technologies
None

Grid and infrastructure
Electricity

Energy technology substitution
Discrete technology choices

Energy service sectors
Transportation, industry, residential and commercial

Land use
Land cover
No land use is simulated in the current version of GEM-E3.

Other resources
Other resources

Emissions and climate
Greenhouse gases
CO_2, CH_4, N_2O, HFCs, CFCs, SF_6

Pollutants
NO_X, SO_X

Climate indicators
None

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

About
Name and version
GENeSYS-MOD 1.0

Institution and users
Technische Universität (TU) Berlin, Germany / German Institute for Economic Research (DIW Berlin), Germany

Model scope and methods
Objective
The Global Energy System Model (GENeSYS-MOD) is an open-source energy system model, based on the Open-Source Energy Modelling System (OSeMOSYS). The aim is to analyse potential pathways and scenarios for the future energy system, for example, for an assessment of climate targets. It incorporates the power, heat, and transportation sectors and specifically considers sector-coupling aspects between these traditionally segregated sectors.

Concept
The model minimizes the total discounted system costs by choosing the cost-optimal mix of generation and sector-coupling technologies for the power, heat, and transportation sectors.

Solution method
Linear program optimization (minimizing total discounted system costs)

Anticipation
Perfect foresight

Temporal dimension
Base year: 2015
Time steps: 2015, 2020, 2030, 2035, 2040, 2045, 2050
Horizon: 2015–2050

Spatial dimension
Number of regions: 10
Europe, Africa, North America, South America, Oceania, China and Mongolia, India, Middle East, Former Soviet Union, Remaining Asian countries (mostly Southeast-Asia)

Policy implementation
Emission tax/pricing, emissions budget, fuel taxes, fuel subsidies, capacity targets, emission standards, energy efficiency standards

Socio-economic drivers
Exogenous drivers
Technical progress (such as efficiency measures), GDP per capita, population

Endogenous drivers
None

Development
None

Macro economy
Economic sectors
None

Cost measures
None

Trade

Energy
Behaviour
None

Resource use
Coal, oil, gas, uranium, biomass

Electricity technologies
Coal, gas, oil, nuclear, biomass, wind (onshore & offshore), solar PV (utility PV & rooftop PV), CSP, geothermal, hydropower, wave & tidal power

Conversion technologies
CHP, hydrogen (electrolysis & fuel cells), electricity & gas storages

Grid and infrastructure
Electricity

Energy technology substitution
Discrete technology choices, expansion and decline constraints, system integration constraints

Energy service sectors
Transportation (split up in passenger & freight), total power demand, heat (divided up in warm water / space heating & process heat)

Land use
Land cover
None

Other resources
Other resources
None

Emissions and climate
Greenhouse gases
CO_2

Pollutants
None

Climate indicators
None

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

About
Name and version
GRAPE-15 1.0

Institution and users
The Institute of Applied Energy, Japan – https://doi.org/10.5547/ISSN0195-6574-EJ-VolSI2006-NoSI3-13

Model scope and methods
Objective
GRAPE is an integrated assessment model with an inter-temporal optimization model, which consists of modules for energy, macro economy, climate, land use and environmental impacts.

Concept
None

Solution method
Partial equilibrium (fixed demand) inter-temporal optimization

Anticipation
Perfect foresight

Temporal dimension
Base year: 2005
Time steps: 5 years
Horizon: 2110

Spatial dimension
Number of regions: 15
Canada, USA, Western Europe, Japan, Oceania, China, Southeast Asia, India, Middle East, Sub-Sahara Africa, Brazil, other Latin America, Central Europe, Eastern Europe, Russia

Policy implementation
Emissions taxes/pricing, cap and trade, land protection

Socio-economic drivers
Exogenous drivers
Population, population age structure, education level, urbanization rate, GDP, income distribution, total factor productivity, autonomous energy efficiency improvements

Endogenous drivers
None

Development
Income distribution in a region (exogenous), urbanization rate (exogenous), education level (exogenous)

Macro economy
Economic sectors
Agriculture, industry, energy, transport, services

Cost measures
GDP loss, welfare loss, consumption loss, energy system costs

Trade
Coal, oil, gas, electricity, bioenergy crops, food crops, non-energy goods, hydrogen

Energy
Behaviour
None

Resource use
Coal (supply curve), conventional oil (supply curve), unconventional oil (supply curve), conventional gas (supply curve), unconventional gas (supply curve), uranium (supply curve), biomass (supply curve), water (process model), land

Electricity technologies
Coal (w/o and w/ CCS), gas (w/o and w/ CCS), oil (w/o and w/ CCS), nuclear, biomass (w/o and w/ CCS), wind (onshore and offshore), solar PV (central and distributed), geothermal, hydroelectric, hydrogen

Conversion technologies
CHP, coal/oil/gas/biomass-to-heat, hydrogen, coal to H_2 (w/o and w/ CCS), oil to H_2 (w/o and w/ CCS), gas to H_2 (w/o and w/ CCS), biomass to H_2 (w/o CCS), nuclear and solar thermochemical, electrolysis, fuel to gas, coal to gas (w/o and w/ CCS), fuel to liquid, coal to liquids (w/o and w/ CCS), gas to liquids (w/o and w/ CCS), biomass to liquids (w/o and w/ CCS), oil refining

Grid and infrastructure
Electricity, Gas, Heat, CO_2,H_2

Energy technology substitution
Discrete technology choices with mostly high substitutability through linear choice (lowest cost), expansion and decline constraints

Energy service sectors
Transportation, industry, residential and commercial

Land use
Land cover
Energy cropland, forest, pastures, built-up area

Other resources
Other resources
Water

Emissions and climate
Greenhouse gases
CO_2, fossil fuels, land use, CH_4, energy, land use, N_2O, energy, HFCs, CFCs, SF_6, CO, energy use

Pollutants
Only for energy, NO_x, SO_x, BC, OC, Ozone

Climate indicators
CO_2e concentration (ppm), radiative Forcing (W m^{-2}), temperature change (°C)

2.SM.2.10 Reference Card – ETP Model

About
Name and version
ETP Model, version 3

Institution and users
International Energy Agency – http://www.iea.org/etp/etpmodel/

Model scope and methods
Objective
The analysis and modelling aim to identify an economical way for society to reach the desired outcomes of reliable, affordable and clean energy. For a variety of reasons, the scenario results do not necessarily reflect the least-cost ideal. The ETP analysis takes into account those policies that have already been implemented or decided. In the short term, this means that deployment pathways may differ from what would be most cost-effective. In the longer term, the analysis emphasizes a normative approach, and fewer constraints governed by current political objectives apply in the modelling. The objective of this methodology is to provide a model for a cost-effective transition to a sustainable energy system.

Concept
Partial equilibrium (fixed energy service and material demands), with the exception for the transport sector, where 'avoid and shift' policies are being considered.

Solution method
Optimization for power, other transformation and industry sectors; simulation for agriculture, residential, services and transport sectors

Anticipation
Inter-temporal (foresight)

Temporal dimension
Base year: 2014
Time steps: 5 years
Horizon: 2060

Spatial dimension
Number of regions: differs between energy sectors (28-39 model regions)
Asian countries except Japan, countries of the Middle East and Africa, Latin American countries, OECD90 and EU (and EU candidate) countries, countries from the Reforming Economies of the Former Soviet Union World, OECD countries, non-OECD countries, Brazil, China, South Africa, Russia, India, ASEAN region countries, USA, European Union (28 member countries), Mexico

Policy implementation
Emission tax/pricing, cap and trade, fuel taxes, fuel subsidies, feed-in-tariff, portfolio standards, capacity targets, emission standards, energy efficiency standards

Socio economic drivers
Exogenous drivers
Population, urbanization rate, GDP, autonomous energy efficiency

improvements

Endogenous drivers
None

Development
None

Macro economy
Economic sectors
Agriculture, industry, residential, services, transport, power, other transformation

Cost measures
None

Trade
Coal, oil, gas, electricity

Energy
Behaviour
None

Resource use
Coal (supply curve), conventional oil (process model), unconventional oil (supply curve), conventional gas (process model), unconventional gas (supply curve), bioenergy (supply curve)

Electricity technologies
Coal (w/o and w/ CCS), gas (w/o and w/ CCS), oil (w/o and w/ CCS) nuclear, biomass (w/o and w/ CCS), solar power (central PV, distributed PV, and CSP), wind power (onshore and offshore), hydroelectric power, ocean power

Conversion technologies
Coal to hydrogen (w/o CCS and w/ CCS), natural gas to hydrogen (w/o CCS and w/ CCS), oil to hydrogen (w/o CCS), biomass to hydrogen (w/o CCS and w/ CCS), coal to liquids (w/o CCS and w/ CCS), gas to liquids (w/o CCS and w/ CCS), bioliquids (w/o CCS and w/ CCS), oil refining, coal to gas (w/o CCS and w/ CCS), oil to gas (w/o CCS and w/ CCS), biomass to gas (w/o CCS and w/ CCS), coal heat, natural gas heat, oil heat , biomass heat, geothermal heat, solarthermal heat, CHP (coupled heat and power)

Grid and infrastructure
Electricity (spatially explicit), gas (aggregate), heat (aggregate), hydrogen (aggregate), CO_2 (spatially explicit), gas spatially explicit for gas pipelines and LNG infrastructure between model regions

Energy technology substitution
Lowest cost with adjustment penalties. Discrete technology choices with mostly high substitutability in some sectors and mostly low substitutability in other sectors.
Expansion and decline constraints.
System integration constraints.

Energy service sectors
Transportation, industry, residential and commercial

Land use
Land cover
Not represented by the model

Other resources
Other resources
None

Emissions and climate
Greenhouse gases
CO_2 fossil fuels (endogenous & controlled)
CO_2 cement (endogenous & controlled)

Pollutants
None

Climate indicators
None

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

About

Name and version

IEA World Energy Model (version 2016)

Institution and users

International Energy Agency - https://www.iea.org/weo/ http://www.iea.org/media/weowebsite/2016/WEM_Documentation_WEO2016.pdf

Model scope and methods

Objective

The model is a large-scale simulation model designed to replicate how energy markets function and is the principal tool used to generate detailed sector-by-sector and region-by-region projections for the World Energy Outlook (WEO) scenarios.

Concept

Partial equilibrium (price elastic demand)

Solution method

Simulation

Anticipation

Mix of `Inter-temporal (foresight)´ and `Recursive-dynamic (myopic)´

Temporal dimension

Base year: 2014
Time steps: 1 year steps
Horizon: 2050

Spatial dimension

Number of regions: 25
United States, Canada, Mexico, Chile, Japan, Korea, OECD Oceania, Other OECD Europe, France, Germany, Italy, United Kingdom, Europe 21 excluding EUG4, Europe 7, Eurasia, Russia, Caspian, China, India, Indonesia, South East Asia (excluding Indonesia), rest of Other Developing Asia, Brazil, other Latin America, North Africa, other Africa South Africa, Middle East

Policy implementation

Emission tax/pricing, cap and trade (global and regional), fuel taxes, fuel subsidies, feed-in-tariff, portfolio standard, capacity targets, emission standards, energy efficiency standards

Socio economic drivers

Exogenous drivers

Population (exogenous), urbanization rate (exogenous), GDP (exogenous)

Endogenous drivers

Autonomous energy efficiency improvements (endogenous)

Development

None

Macro economy

Economic sectors

Agriculture (economic), industry (physical & economic), services (economic), energy (physical & economic)

Cost measures

Energy system cost mark-up

Trade

Coal, oil, gas, bioenergy crops, emissions permits

Energy

Behaviour

Price elasticity

Resource use

Coal (process model), conventional oil (process model), unconventional oil (process model), conventional gas (process model), unconventional gas (process model), bioenergy (process model)

Electricity technologies

Coal, gas, oil, nuclear, geothermal, bioenergy, wind (onshore and offshore), solar PV (central and distributed), CCS*, CSP, Hydropower, ocean power

*Note: CCS can be combined with coal, gas and biomass power generation technologies

Conversion technologies

Natural gas to hydrogen w/o CCS, coal to liquids w/o CCS, coal to gas w/o CCS, coal heat, natural gas heat, oil heat, bioenergy heat, geothermal heat, solarthermal heat, CHP (coupled heat and power)

Grid and infrastructure

Electricity (aggregate), gas (aggregate)

Energy technology substitution

Logit choice model, weibull function, discrete technology choices with mostly high substitutability in some sectors and mostly low substitutability in other sectors, expansion and decline constraints, system integration constraints

Energy service sectors

Transportation, industry, residential, commercial

Land use

Land cover

Not covered by the model

Other resources

Other resources

Emissions and climate

*Greenhouse gases**

CO_2, CH_4, N_2O, HFCs (exogenous), CFCs (exogenous), SF_6 (exogenous)

*Pollutants**
NO_x, SO_x, BC, OC, CO, NH_3, VOC

*NOTE: Non-energy CO_2, non-energy CH_4, non-energy N_2O, CFC, HFC, SF_6, CO, NOx, VOC, SO_2, are assumptions-based and not disaggregated (only total emissions are available).

Climate indicators
CO_2e concentration (ppm), radiative forcing (W m^{-2}), temperature change (°C)

2.SM.2.12 Reference Card – IMACLIM

About

Name and version
IMACLIM 1.1 (Advance), IMACLIM-NLU 1.0 (EMF33)

Institution and users
Centre International de Recherche sur l'Environnement et le Développement (CIRED), France, http://www.centre-cired.fr.
Société de Mathématiques Appliquées et de Sciences Humaines (SMASH), France, http://www.smash.fr.

Model scope and methods

Objective
Imaclim-R is intended to study the interactions between energy systems and the economy to assess the feasibility of low-carbon development strategies and the transition pathway towards a low-carbon future.

Concept
Hybrid: general equilibrium with technology explicit modules. Recursive dynamics: each year the equilibrium is solved (system of non-linear equations), in between years the parameters for the equilibrium evolve according to specified functions.

Solution method
Imaclim-R is implemented in Scilab and uses the function fsolve from a shared C++ library to solve the static equilibrium system of non-linear equations.

Anticipation
Recursive dynamics: each year the equilibrium is solved (system of non-linear equations), in between years, the parameters for the equilibrium evolve according to specified functions.

Temporal dimension
Base year: 2001
Time steps: annual
Horizon: 2050 or 2100

Spatial dimension
Number of regions: 12
USA, Canada, Europe, China, India, Brazil, Middle East, Africa, Commonwealth of Independent States, OECD Pacific, rest of Asia, rest of Latin America

Policy implementation
Baseline does not include explicit climate policies. Climate/energy policies can be implemented in a number of ways, depending on the policy. A number of general or specific policy choices can be modelled, including: emissions or energy taxes, permit trading, specific technology subsidies, regulations, technology and/or resource constraints

Socio economic drivers

Exogenous drivers
Labour productivity, energy technical progress, population, active population

Note: Our model growth engine is composed of exogenous trends of active population growth and exogenous trends of labour productivity growth. The two sets of assumptions on demography and labour productivity, although exogenous, only prescribe natural growth. Effective growth results endogenously from the interaction of these driving forces with short-term constraints: (i) available capital flows for investments and (ii) rigidities, such as fixed technologies, immobility of the installed capital across sectors or rigidities in real wages, which may lead to partial utilization of production factors (labour and capital).

Endogenous drivers
None

Development
GDP per capita

Macro economy
Economic sectors
Agriculture, industry, energy, transport, services, construction
Note: The energy sector is divided into five sub-sectors: oil extraction, gas extraction, coal extraction, refinery, power generation. The transport sector is divided into three sub-sectors: terrestrial transport, air transport, water transport. The industry sector has one sub-sector: Energy intensive industry.

Cost measures
GDP loss, welfare loss, consumption loss, energy system costs

Cost measures
GDP loss, welfare loss, consumption loss, energy system costs

Trade
Coal, oil, gas, electricity, bioenergy crops, capital, emissions permits, non-energy goods, refined liquid fuels

Energy
Behaviour
Price response (via elasticities), and non-price drivers (infrastructure and urban forms conditioning location choices, different asymptotes on industrial goods consumption saturation levels with income rise, speed of personal vehicle ownership rate increase, speed of residential area increase).

Resource use
Coal, oil, gas, biomass

Electricity technologies
Coal, gas, oil, nuclear, biomass, wind, solar PV, CCS

Conversion technologies
Fuel to liquid

Grid and infrastructure
Electricity

Energy technology substitution
Discrete technology choices, expansion and decline constraints, system integration constraints

Energy service sectors
Transportation, industry, residential and commercial, agriculture

Land use
Land cover
Cropland, forest, extensive pastures, intensive pastures, inaccessible pastures, urban areas, unproductive land

Note: MACLIM 1.1 (Advance): Bioenergy production is determined by the fuel and electricity modules of Imaclim-R using supply curves from Hoogwijk et al. (2009) (bioelectricity) and IEA (biofuel).

IMACLIM-NLU 1.0 (EMF33): In this version the Imaclim-R model is linked to the land-use mode Nexus Land use. Bioenergy demand level is determined by the fuel and electricity modules of Imaclim-R. The Nexus Land use gives the corresponding price of biomass feedstock, taking into account the land constraints and food production The production of biomass for electricity and ligno-cellulosic fuels is located on marginal lands (i.e., less fertile or accessible lands). By increasing the demand for land, and spurring agricultural intensification, Bioenergy propels land and food prices.

Other resources
Other resources
None

Emissions and climate
Greenhouse gases
CO_2

Pollutants
None

Climate indicators
None

2.SM.2.13 Reference Card – IMAGE

About

Name and version

IMAGE framework 3.0

Institution and users

Utrecht University (UU), Netherlands, http://www.uu.nl.
PBL Netherlands Environmental Assessment Agency (PBL), Netherlands, http://www.pbl.nl.

Model scope and methods

Objective

IMAGE is an ecological–environmental model framework that simulates the environmental consequences of human activities worldwide. The objective of the IMAGE model is to explore the long-term dynamics and impacts of global changes that result. More specifically, the model aims to analyse interactions between human development and the natural environment to gain better insight into the processes of global environmental change, to identify response strategies to global environmental change based on assessment of options, and to indicate key inter-linkages and associated levels of uncertainty in processes of global environmental change.

Concept

The IMAGE framework can best be described as a geographically explicit integrated assessment simulation model, focusing on a detailed representation of relevant processes with respect to human use of energy, land and water in relation to relevant environmental processes.

Solution method

Recursive dynamic solution method

Anticipation

Simulation modelling framework, without foresight. However, a simplified version of the energy/climate part of the model (called FAIR) can be run prior to running the framework to obtain data for climate policy simulations.

Temporal dimension

Base year: 1970
Time steps: 1-5 year time step
Horizon: 2100

Spatial dimension

Number of regions: 26
Canada, USA, Mexico, rest of Central America, Brazil, rest of South America, Northern Africa, Western Africa, Eastern Africa, South Africa, Western Europe, Central Europe, Turkey, Ukraine +, Asian-Stan, Russia +, Middle East, India +, Korea, China +, Southeastern Asia, Indonesia +, Japan, Oceania, rest of South Asia, rest of Southern Africa

Policy implementation

Key areas where policy responses can be introduced in the model are: Climate policy, energy policies (air pollution, access and energy security), land use policies (food), specific policies to project biodiversity, measures to reduce the imbalance of the nitrogen cycle

Socio-economic drivers

Exogenous drivers

Exogenous GDP, GDP per capita, population

Endogenous drivers

Energy demand, renewable price, fossil fuel prices, carbon prices, technology progress, energy intensity, preferences, learning by doing, agricultural demand, value added

Development

GDP per capita, income distribution in a region, urbanization rate

Note: GDP per capita and income distribution are exogenous

Macro economy

Economic sectors

Note: No explicit economy representation in monetary units. Explicit economy representation in terms of energy is modelled (for the agriculture, industry, energy, transport and built environment sectors)

Cost measures

Area under MAC, energy system costs

Trade

Coal, oil, gas, uranium, bioenergy crops, food crops, emissions permits, non-energy goods, bioenergy products, livestock products

Energy

Behaviour

In the energy model, substitution among technologies is described in the model using the multinomial logit formulation. The multinomial logit model implies that the market share of a certain technology or fuel type depends on costs relative to competing technologies. The option with the lowest costs gets the largest market share, but in most cases not the full market. We interpret the latter as a representation of heterogeneity in the form of specific market niches for every technology or fuel.

Resource use

Coal, oil, gas, uranium, biomass

Note: Distinction between traditional and modern biomass

Electricity technologies

Coal w/ CCS, coal w/o CCS, gas w/ CCS, gas w/o CCS, oil w/ CCS, oil w/o CCS, nuclear, biomass w/ CCS, biomass w/o CCS, wind, solar PV, CSP, hydropower, geothermal

Note: wind: onshore and offshore; coal: conventional, IGCC, IGCC + CCS, IGCC + CHP, IGCC + CHP + CCS; oil: conventional, OGCC, OGCC + CCS, OGCC + CHP, OGCC + CHP + CCS); natural gas: conventional, CC, CC + CCS, CC + CHP, CC + CHP + CCS; biomass: conventional, CC, CC + CCS, CC + CHP, CC + CHP + CCS; hydropower and geothermal: exogenous

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Conversion technologies
CHP, hydrogen

Grid and infrastructure
Electricity

Energy technology substitution
Discrete technology choices, expansion and decline constraints, system integration constraints

Energy service sectors
Transportation, industry, residential and commercial

Land use
Land cover
Forest, cropland, grassland, abandoned land, protected land

Other resources
Other resources
Water, metals, cement

Emissions and climate
Greenhouse gases
CO_2, CH_4, N_2O, HFCs, CFCs, SF_6, PFCs

Pollutants
NO_x, SO_x, BC, OC, ozone, VOC, NH_3, CO

Climate indicators
CO_2e concentration (ppm), radiative forcing (W m^{-2}), temperature change (°C)

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

About
Name and version
MERGE-ETL 6.0

Institution and users
Paul Scherrer Institut
https://www.psi.ch/eem/ModelsEN/2012MergeDescription.pdf
https://www.psi.ch/eem/ModelsEN/2014MergeCalibration.pdf

Model scope and methods
Objective
MERGE (Model for Evaluating Regional and Global Effects of GHG reductions policies) is an integrated assessment model originally developed by Manne et al. (1995). It divides the world in geopolitical regions, each one represented by two coupled submodels describing the energy and economic sectors, respectively. MERGE acts as a global social planner with perfect foresight and determines the economic equilibrium in each region that maximizes global welfare, defined as a linear combination of the current and future regional welfares. Besides these regional energy–economic submodels, and linked to them, MERGE includes global submodels of greenhouse gas emissions and the climate to allow the analysis of the effectiveness and impacts of climate policies and the role of technologies to realize climate targets. The model is sufficiently flexible to explore views on a wide range of contentious issues: costs of abatement, damages of climate change, valuation and discounting.

Concept
The MERGE-ETL model is a hard-linked hybrid model as the energy sectors are fully integrated with the rest of the economy. The model combines a bottom-up description of the energy system disaggregated into electric and non-electric sectors, a top-down economic model based on macroeconomic production functions, and a simplified climate cycle model. The energy sectors endogenously account for technological change with explicit representation of two-factor learning curves.

Solution method
General equilibrium (closed economy). Two different solutions can be produced: a cooperative globally optimal solution and a non-cooperative solution equivalent to Nash equilibrium. It is programmed in GAMS and uses the CONOPT solver.

Anticipation
Inter-temporal (foresight) or myopic.

Temporal dimension
Base year: 2015
Time steps: 10 years
Horizon: 2015-2100

Spatial dimension
Number of regions: 10
EUP (European Union), RUS (Russia), MEA (Middle East), IND (India), CHI (China), JPN (Japan), CANZ (Canada, Australia and New

Zealand), USA (United States of America), ROW (Rest of the World), SWI (Switzerland)

Policy implementation
Emission tax/pricing, cap and trade, fuel taxes, fuel subsidies, feed-in-tariff, portfolio standard, capacity targets

Socio economic drivers

Exogenous drivers
Population, population age structure, autonomous energy efficiency improvements

Development
GDP

Macro economy

Economic sectors
One final good, electric and non-electric demand sectors

Cost measures
GDP loss, welfare loss, consumption loss, area under mac, energy system costs

Trade
Non-energy goods, coal, oil, gas, uranium, bioenergy crops, emissions permits

Energy

Behaviour
Considered in side-constraints controlling technology deployment rates

Resource use
Coal, conventional oil, unconventional oil, conventional gas, unconventional gas, uranium, bioenergy
Note: Cost-supply curves for the different resources are considered

Electricity technologies
Coal, gas, oil, nuclear, biomass, wind, solar PV, hydrogen
Note: CCS can be combined with coal, gas and biomass power generation technologies

Conversion technologies
Hydrogen,fuel to liquids
Note: CCS can be combined with coal, gas and biomass technologies

Grid and infrastructure
Electricity, gas, CO_2, H_2

Energy technology substitution
Expansion and decline constraints, system integration constraints, early technology retirement

Energy service sectors
Electric and non-electric demand that is further disaggregated to seven energy sectors/fuels, namely coal, oil, gas, biofuels, hydrogen, solar and heat

Land use

Land cover

Other resources

Other resources

Emissions and climate

Greenhouse gases, CO_2, CH_4, N_2O, HFCs, SF_6

Pollutants
None

Climate indicators
CO_2e concentration (ppm), radiative forcing (W m^{-2}), temperature change (°C), climate damages $ or equivalent

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

About

Name and version

MESSAGE-GLOBIOM 1.0 and MESSAGEix-GLOBIOM 1.0

Institution and users

International Institute for Applied Systems Analysis (IIASA), Austria, global model description: http://data.ene.iiasa.ac.at/message-globiom/. Model documentation and code (MESSAGEix) http://messageix.iiasa.ac.at

Main users: IIASA, the MESSAGE model is distributed via the International Atomic Energy Agency (IAEA) to member countries, the new MESSAGEix model is available as an open source tool via GitHub (https://github.com/iiasa/message_ix)

Model scope and methods

Objective

MESSAGE-GLOBIOM is an integrated assessment framework designed to assess the transformation of the energy and land systems vis-a-vis the challenges of climate change and other sustainability issues. It consists of the energy model MESSAGE, the land use model GLOBIOM, the air pollution and GHG model GAINS, the aggregated macroeconomic model MACRO and the simple climate model MAGICC.

Concept

Hybrid model (energy engineering and land use partial equilibrium models soft-linked to macroeconomic general equilibrium model)

Solution method

Hybrid model (linear program optimization for the energy systems and land use modules, non-linear program optimization for the macroeconomic module)

Anticipation

Myopic/Perfect Foresight (MESSAGE can be run both with perfect foresight and myopically, while GLOBIOM runs myopically)

Temporal dimension

Base year: 2010

Time steps: 1990, 1995, 2000, 2005, 2010, 2020, 2030, 2040, 2050, 2060, 2070, 2080, 2090, 2100, 2110

Horizon: 1990-2110

Spatial dimension

Number of regions: 11+1

AFR (Sub-Saharan Africa), CPA (Centrally Planned Asia & China), EEU (Eastern Europe), FSU (Former Soviet Union), LAM (Latin America and the Caribbean), MEA (Middle East and North Africa), NAM (North America), PAO (Pacific OECD), PAS (Other Pacific Asia), SAS (South Asia), WEU (Western Europe), GLB (international shipping)

Policy implementation

GHG and energy taxes; GHG emission cap and permits trading; energy taxes and subsidies; micro-financing (for energy access analysis); regulation: generation capacity, production and share targets

Socio economic drivers

Exogenous drivers

Labour productivity, energy technical progress, GDP per capita, population

Endogenous drivers

None

Development

GDP per capita, income distribution in a region, number of people relying on solid cooking fuels

Macro economy

Economic sectors

Note: MACRO represents the economy in a single sector with the production function including capital, labour and energy nests

Cost measures

GDP loss, consumption loss, area under marginal abatement cost (MAC) curve, energy system costs

Trade

Coal, oil, gas, uranium, electricity, food crops, emissions permits

Note: bioenergy is only traded after processing to a secondary fuel (e.g., liquid biofuel)

Energy

Behaviour

Non-monetary factors of decision making (e.g., behavioural impacts) are represented in MESSAGE via so-called inconvenience costs. These are generally included in the consumer-dominated energy end-use sectors (transportation sector, residential and commercial sector) and are particularly relevant in the modelling of energy access in developing countries.

Resource use

Coal, oil, gas, uranium, biomass

Note: modern and traditional applications of biomass are distinguished

Electricity technologies

Coal w /o CCS, coal w/ CCS, gas w/o CCS, gas w/ CCS, oil w/o CCS, biomass w/o CCS, biomass w/ CCS, nuclear, wind onshore, wind offshore, solar PV, CSP, geothermal, hydropower

Note: CCS can be combined with coal, gas and biomass power generation technologies

Conversion technologies

CHP, hydrogen, fuel to gas, fuel to liquid

Note: CHP can be combined with all thermal power plant types; hydrogen can be produced from coal, gas and biomass feedstocks and electricity; fuel to liquids is represented for coal, gas and biomass feedstocks; and fuel to gas is represented for coal and biomass feedstocks

Grid and infrastructure

Electricity, Gas, Heat, CO_2, Hydrogen

Energy technology substitution

Discrete technology choices, expansion and decline constraints, system integration constraints

Energy service sectors

Transportation, Industry, Residential and commercial

Note: non-energy use (feedstock) of energy carriers is separately represented, but generally reported under industry

Land use

Land cover

Forest (natural/managed), short-rotation plantations, cropland, grassland, other natural land

Other resources

Other resources

Water, cement

Note: cement is not modelled as a separate commodity, but process emissions from cement production are represented

Emissions and climate

Greenhouse gases

CO_2, CH_4, N_2O, HFCs, CFCs, SF_6

Pollutants

NO_x, SO_x, BC, OC, CO, NH_3, VOC

Climate indicators

CO_2e concentration (ppm), radiative forcing (W m^{-2}), temperature change (°C)

2.SM.2.16 Reference Card – POLES

About

Name and version

POLES ADVANCE (other versions are in use in other applications)

Institution and users

JRC - Joint Research Centre - European Commission (EC-JRC), Belgium, http://ec.europa.eu/jrc/en/poles.

Main users: - European Commission JRC; Université de Grenoble UPMF, France - Enerdata

Model scope and methods

Objective

POLES was originally developed to assess energy markets, combining a detailed description of energy demand, transformation and primary supply for all energy vectors. It provides full energy balances on a yearly basis using frequent data updates so as to deliver robust forecasts for both short- and long-term horizons. It has quickly been used, since the late 90s, to assess energy-related CO_2 mitigation policies. Over time, other GHG emissions have been included (energy and industry non-CO_2 from the early 2000s), and linkages with agricultural and land use models have been progressively implemented.

Concept

Partial equilibrium

Solution method

Recursive simulation

Anticipation

Myopic

Temporal dimension

Base year: 1990-2015 (data up to current time –1/–2)

Time steps: yearly

Horizon: 2050–2100

Spatial dimension

Number of regions: 66

Policy implementation

Energy taxes per sector and fuel, carbon pricing, feed-in-tariffs, green certificates, low interest rates, investment subsidies, fuel efficiency standards in vehicles and buildings, white certificates

Socio economic drivers

Exogenous drivers

Exogenous GDP, population

Endogenous drivers

Value added, mobility needs, fossil fuel prices, buildings surfaces

Development

GDP per capita, urbanization rate

Macro economy

Economic sectors
Agriculture, industry, services

Cost measures
Area under MAC, energy system costs
Note: Investments: supply-side only

Trade
Coal, oil, gas, bioenergy crops, liquid biofuels

Energy

Behaviour
Activity drivers depend on income per capita and energy prices via elasticities. Energy demand depends on activity drivers, energy prices and technology costs. Primary energy supply depends on remaining resources, production cost and price effects.

Resource use
Coal, oil, gas, uranium, biomass

Electricity technologies
Coal, gas, oil, nuclear, biomass, wind, solar PV, CCS, hydropower, geothermal, solar CSP, ocean

Conversion technologies
CHP, hydrogen, fuel to liquid

Grid and infrastructure
Gas, H_2

Energy technology substitution
None

Energy service sectors
Transportation, industry, residential and commercial

Land use

Land cover
Cropland, forest, grassland, urban areas, desert

Other resources

Other resources
Metals
Note: Steel tons

Emissions and climate

Greenhouse gases
CO_2, CH_4, N_2O, HFCs, SF_6, PFCs

Pollutants
None

Climate indicators
None

2.SM.2.17 Reference Card – REMIND - MAgPIE

About

Name and version
REMIND 1.7 – MAgPIE 3.0

Institution and users
Potsdam Institut für Klimafolgenforschung (PIK), Germany,
https://www.pik-potsdam.de/remind
https://www.pik-potsdam.de/magpie

Model scope and methods

Objective
REMIND-MAgPIE is an integrated assessment modeling framework to assess energy and land use transformations and their implications for limiting global warming and achieving sustainable development goals.

REMIND (Regionalized Model of Investment and Development) is a global multiregional model incorporating the economy, the climate system and a detailed representation of the energy sector. It allows analysing technology options and policy proposals for climate mitigation, and models regional energy investments and interregional trade in goods, energy carriers and emissions allowances.

MAgPIE (Model of Agricultural Production and its Impacts on the Environment) is a global multiregional economic land-use optimization model designed for scenario analysis up to the year 2100. MAgPIE provides a holistic framework to explore future transformation pathways of the land system, including multiple trade-offs with ecosystem services and sustainable development.

Concept
REMIND: Hybrid model that couples an economic growth model with a detailed energy system model and a simple climate model.

MAgPIE: Gridded land-use optimization model with 10 socio-economic world regions. MAgPIE takes regional economic conditions, such as demand for agricultural commodities, technological development, and production costs, as well as spatially explicit data on potential crop yields, carbon stocks and water constraints (from the dynamic global vegetation model LPJmL), under current and future climatic conditions into account.

Solution method
REMIND: Inter-temporal optimization that, based on a Ramsey-type growth model, maximizes regional welfare in a Nash equilibrium or, alternatively, Pareto optimum using the Negishi algorithm.

MAgPIE: Partial equilibrium model of the agricultural sector with recursive-dynamic optimization. The objective function of MAgPIE is the fulfilment of agricultural demand for 10 world regions at minimum global costs under consideration of biophysical and socio-economic constraints. Major cost types in MAgPIE are factor requirement costs (capital, labor, fertilizer), land conversion costs, transportation costs to the closest market, investment costs for yield-increasing technological change (TC) and costs for GHG emissions in mitigation scenarios.

REMIND and MAgPIE are coupled by exchanging greenhouse gas prices and bioenergy demand from REMIND to MAgPIE, and bioenergy prices and AFOLU greenhouse gas emissions from MAgPIE to REMIND, and iterating until an equilibrium of prices and quantities is established.

Anticipation
REMIND: Perfect Foresight
MAgPIE: Myopic

Temporal dimension
REMIND:
Base year: 2005
Time steps: flexible time steps, default is 5-year time steps until 2060 and 10-year time steps until 2100; period from 2100–2150 is calculated to avoid distortions due to end effects, but typically only the time span 2005–2100 is used for model applications.

MAgPIE:
Base year: 1995
Time steps: 5 and/or 10 years
Horizon: 1995–2100

Spatial dimension
Number of regions: 11
AFR - Sub-Saharan Africa (excluding South Africa)
CHN - China
EUR - European Union
JPN - Japan
IND - India
LAM - Latin America
MEA - Middle East, North Africa, and Central Asia
OAS - other Asian countries (mainly Southeast Asia)
RUS - Russia
ROW - rest of the World (Australia, Canada, New Zealand, Non-EU Europe, South Africa)
USA - United States of America
Note: MAgPIE operates on 10 socio-economic world regions which are mapped to REMIND-defined regions.

Policy implementation
REMIND: Pareto-optimal achievement of policy targets on temperature, radiative forcing, GHG concentration, or cumulative carbon budgets. Alternatively, calculation of Nash equilibrium without internalized technology spillovers. Possibility to analyse changes in expectations about climate policy goals as well as pre-specified policy packages until 2030/2050, including, for example, energy capacity and efficiency targets, renewable energy quotas, carbon and other taxes, and energy subsidies

MAgPIE: 1st- and 2nd-generation bioenergy, pricing of GHG emissions from land-use change (CO_2) and agricultural land use (CH_4, N_2O), land-use regulation, REDD+ policies, afforestation, agricultural trade policies

Socio economic drivers

Exogenous drivers
REMIND: Labour productivity, energy efficiency parameters of the production function, population.

MAgPIE: Demand for bioenergy, food, feed, and material demand from the agricultural sector.

Endogenous drivers
REMIND: Investments in industrial capital stock and specific energy technology capital stocks. Endogenous learning-by-doing for wind and solar power as well as electric and fuel cell vehicle technologies (global learning curve, internalized spillovers).

MAgPIE: Investments in agricultural productivity, land conversion and (re)allocation of agricultural production.

Development
REMIND: GDP per capita
MAgPIE: GDP per capita

Macro economy (REMIND)

Economic sectors
Note: The macroeconomic part contains a single sector representation of the entire economy. A generic final good is produced from capital, labour, and different final energy types

Cost measures
GDP loss, welfare loss, consumption loss

Trade
Coal, oil, gas, uranium, bioenergy crops, capital, emissions permits, non-energy goods

Energy (REMIND)

Behaviour
Energy demands react to energy prices and technology costs. Price response of final energy demand 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
Coal, oil, gas, uranium, biomass

Electricity technologies
Coal (with and w/o CCS), gas (with and w/o CCS), oil (w/o CCS), nuclear, biomass (with and w/o CCS), wind, solar PV, solar CSP, hydropower, geothermal, hydrogen

Conversion technologies
CHP, Heat pumps, hydrogen (from fossil fuels and biomass with and w/o CCS; electrolytic hydrogen), fuel to gas, fuel to liquid (from fossil fuels and biomass with and w/o CCS), heat plants

Grid and infrastructure

Electricity, Gas, Heat, CO_2, H_2

Note: Generalized transmission and distribution costs are included, but not modelled on an explicit spatial level. Regionalized additional grid and storage costs for renewable integration are included.

Energy technology substitution

Discrete technology choices with high to full substitutability, expansion and decline constraints, system integration constraints

Note: Expansion and decline, and system integration are influenced though cost mark-ups rather than constraints.

Energy service sectors

Transportation, industry, residential and commercial

Note: In older versions of REMIND (REMIND 1.6 and earlier), the industry and residential and commercial sectors are not treated separately but represented jointly by one stationary sector (referred to as 'Other Sector').

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Land use (MAgPIE)

MAgPIE allocates land use to fulfil competing demands for commodities, feed, carbon storage, land conservation and environmental protection. Land use is broadly categorized in cropland, forest land, pasture land, and other natural land. Regional food energy demand is defined for an exogenously given population in 16 food energy categories, based on regional diets. Future trends in food demand are derived from a cross-country regression analysis, based on future scenarios on GDP and population growth. MAgPIE takes technological development and production costs as well as spatially explicit data on potential crop yields, land and water constraints (from LPJmL) into account. It includes agricultural trade with different levels of regional self-sufficiency constraints. MAgPIE calculates the following AFOLU GHG emissions: CO_2 from land use change (including changes to soil and plant carbon content), N_2O from fertilizing agricultural soils and manure management, and CH_4 from enteric fermentation, manure management and rice cultivation.

Other resources

Other resources

Cement

Note: Cement production is not explicitly modelled, but emissions from cement production are accounted for.

Emissions and climate

Greenhouse gases

CO_2, CH_4, N_2O, HFCs, PFCs, SF_6

Pollutants

NO_x, SO_x, BC, OC, ozone, CO, VOC, NH_3

Note: Ozone is not modelled as emission but is an endogenous result of atmospheric chemistry.

Climate indicators

CO_2 concentration (ppm), other GHG concentrations, radiative forcing (W m^{-2}), temperature change (°C)

Note: Different emissions are accounted for with different levels of detail depending on the types and sources of emissions (directly by source, via marginal abatement cost (MAC) curves, by econometric estimates, exogenous).

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

About

Name and version

Shell World Energy Model 2018

2018 Edition (Version 2.10 series)

Institution and users

Shell Corporation B.V., www.shell.com/scenariosenergymodels

Model scope and methods

Objective

Exploratory simulations of plausible scenarios, covering both short-term drivers and momentum, together with the capability for long-term transformation of the energy system.

Concept

Partial equilibrium (price elastic demand)

Solution method

Simulation

Anticipation

Recursive-dynamic (myopic)

Temporal dimension

Base year: 2017

Time steps: 1 year steps

Horizon: 2100

Spatial dimension

Number of regions: 100 (= 82 top countries + 18 rest of the world regions)

Policy implementation

Emission tax/pricing, cap and trade, fuel taxes, fuel subsidies, energy efficiency standards

Socio economic drivers

Exogenous drivers

Population

Autonomous Energy Efficiency Improvements

Endogenous drivers

None

Development

None

Macro economy

Economic sectors

Number of sectors: 14

Industry, services, energy, energy service (sector-specific) and energy demand (in EJ) for each sector

Cost measures

None

Trade
Coal, oil, gas, bioenergy crops

Energy
Behaviour
None

Resource use
Coal, conventional oil (process model), unconventional oil (process model), conventional gas (process model), unconventional gas (process model), bioenergy (fixed)

Electricity technologies
Coal (w/o CCS and w/ CCS), gas (w/o CCS and w/ CCS), oil (w/o CCS and w/ CCS), bioenergy (w/o CCS and w/ CCS), geothermal power, nuclear power, solar power (central PV, distributed PV, CSP), wind power, hydroelectric power, ocean power

Conversion technologies
Coal to hydrogen (w/o CCS and w/ CCS), natural gas to hydrogen (w/o CCS and w/ CCS), oil to hydrogen (w/o CCS and w/ CCS), biomass to hydrogen (w/o CCS and w/ CCS), nuclear thermochemical hydrogen electrolysis, coal to liquids (w/o CCS and w/ CCS), gas to liquids (w/o CCS and w/ CCS), bioliquids (w/o CCS and w/ CCS), oil refining, coal to gas (w/o CCS and w/ CCS), oil to gas (w/o CCS and w/ CCS), biomass to gas (w/o CCS and w/ CCS), coal heat, natural gas heat, oil heat, biomass heat, geothermal heat, solarthermal heat

Grid and infrastructure
None

Energy technology substitution
Logit choice model, discrete technology choices with mostly high substitutability, mostly a constrained logit model; some derivative choices (e.g., refinery outputs) have pathway dependent choices, constraints are imposed both endogenously and after off-model analysis

Energy service sectors
Transportation, industry, residential and commercial

Land use
Land cover
None

Other resources
Other resources
None

Emissions and climate
Greenhouse gases, CO_2 fossil fuels (endogenous & uncontrolled)

Pollutants
None

Climate indicators
None

2.SM.2.19 Reference Card – WITCH

About
Name and version
WITCH

Institution and users
Fondazione Eni Enrico Mattei (FEEM), Italy, http://www.feem.it.
Centro Euro-Mediterraneo sui Cambiamenti Climatici (CMCC), Italy, http://www.cmcc.it.
http://www.witchmodel.org/

Model scope and methods
Objective
WITCH evaluates the impacts of climate policies on global and regional economic systems and provides information on the optimal responses of these economies to climate change. The model considers the positive externalities from leaning-by-doing and learning-by-researching in the technological change.

Concept
Hybrid: Economic optimal growth model, including a bottom-up energy sector and a simple climate model, embedded in a 'game theory' framework.

Solution method
Regional growth models solved by non-linear optimization and game theoretic setup solved by tatonnement algorithm (cooperative solution: Negishi welfare aggregation, non-cooperative solution: Nash equilibrium)

Anticipation
Perfect foresight

Temporal dimension
Base year: 2005
Time steps: 5
Horizon: 2150

Spatial dimension
Number of regions: 14
cajaz: Canada, Japan, New Zealand
china: China, including Taiwan
easia: South East Asia
india: India
kosau: South Korea, South Africa, Australia
laca: Latin America, Mexico and Caribbean
indo: Indonesia
mena: Middle East and North Africa
neweuro: EU new countries + Switzerland + Norway
oldeuro: EU old countries (EU-15)
sasia: South Asia
ssa: Sub Saharan Africa
te: Non-EU Eastern European countries, including Russia
usa: United States of America

Policy implementation
Quantitative climate targets (temperature, radiative forcing, concentration), carbon budgets, emissions profiles as optimization constraints, carbon taxes, allocation and trading of emission permits, banking and borrowing, subsidies, taxes and penalty on energies sources.

Socio economic drivers
Exogenous drivers
Total factor productivity, labour productivity, capital technical progress

Development
None

Macro economy
Economic sectors
Energy, other
Note: A single economy sector is represented. Production inputs are capital, labour and energy services, accounting for the energy sector split into 8 energy technologies sectors (coal, oil, gas, wind and solar, nuclear, electricity and biofuels).

Cost measures
GDP loss, welfare loss, consumption loss, energy system costs

Trade
Coal, oil, gas, emissions permits

Energy
Resource use
Coal, oil, gas, uranium, biomass

Electricity technologies
Coal, gas, oil, nuclear, biomass, wind, solar PV, CCS

Conversion technologies
None

Grid and infrastructure
Electricity, CO_2

Energy technology substitution
Expansion and decline constraints, system integration constraints

Energy service sectors
Transportation

Land use
Land cover
Cropland, forest
Note: Bioenergy related cost and emissions are obtained by soft linking with the GLOBIOM model.

Other resources
Other resources
Water

Emissions and climate
Greenhouse gases, CO_2, CH_4, N_2O, HFCs, CFCs, SF_6

Pollutants
NO_x, SO_x, BC, OC

Climate indicators
CO_2e concentration (ppm), radiative forcing (W m^{-2}), temperature change (°C), limate damages $ or equivalent