

A Detailed Overview and Consistent Classification of Climate-Economy Models



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Abstract The proliferation and growing variety of climate-economy models and what are known as integrated assessment models (IAMs) can make it difficult for someone interested in following the debate to place any specific model, or the discussion about the merits of one or another, into a broader context. The literature related to climate-economy modelling is already vast: apart from a very large number of models and an even larger number of applications, there already exist many good surveys comparing—inter alia—modelling frameworks, model assumptions and model results. The objective of this chapter is to provide a simple overview and organising scheme of this modelling world by delving into the characteristics of more than 60 individual IAMs towards describing the main ways in which certain classes or groups of climate-economy models differ from one another. In contrast to other more detailed or narrowly focused “overviews” and literature reviews, this analysis takes less for granted and aims at providing an initial understanding of generic model structures. After briefly discussing some principles of classification that can help organise this often daunting modelling world, the chapter offers descriptions and comparisons of the main classes of models.

Keywords Climate policy · Integrated assessment models · Equilibrium · Macroeconometric · Energy systems · Climate-economy modelling · Optimal growth · Uncertainty

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1 Introduction

Many modelling frameworks have been developed to provide an understanding of the drivers of climate change and to assist policy formation (Flamos 2016). When climate change emerged as a serious issue in the 1970s, there were no theoretical tools that could provide a more integrated understanding of the phenomenon or provide richer insights into policy response. Models of physical dimensions of the climate system (mostly ecosystem models) were extended to consider the processes by which greenhouse gas emissions were generated and could be limited. General circulation models that dealt with atmospheric parts of the climate system were being linked to ocean models. Economists were modifying global energy-economy analysis to project greenhouse gas emissions, considering ways to reduce them and incorporating aggregated physical dimensions of the climate system. Scientists from different disciplines were linking models and analyses to provide a more integrated understanding of different facets of a highly complex interrelated phenomenon (Weyant 2009).

At a broad level, we can see the following interlinked chain of interactions. Human-induced climate change results from an increase in GHG emissions and their levels of concentration in the atmosphere. Climate science tells us how different concentration levels of GHGs may affect the temperature, precipitation, cloud formation, wind and sea level rise. These changes in turn result in various physical, environmental and social impacts like change in crop yields, water supply, species loss and migration. These impacts can then be translated into monetary terms, or processed through a model of the economy, to give a single measure of the economic cost of climate change. As these changes take place over time, models attempt to project parts or the whole dynamic process of increasing emissions, temperature changes, physical impacts and economic damages. The economy is not only affected by climate change, but it is also the perpetrator of climate change as growth in production and consumption gives rise to more GHG emissions. The most important part of the economy that determines the rate of emissions is the energy system or the forms and uses of energy. Each part of this climate-economy interaction is characterised by uncertainty (Papadelis et al. 2013) and some degree of scientific disagreement.

Various ways of climate-economy modelling can to a large extent be understood by the different ways in which they model parts of this highly interconnected process. Figure 1 below provides a depiction of climate-economy dynamics, identifying four key modules of climate-economy modelling. The climate module describes the link between GHG emission, atmospheric concentrations and the resulting variation in temperature and other climatic changes (precipitation, cloud cover, extreme weather events, climate discontinuities, etc.). The impacts module

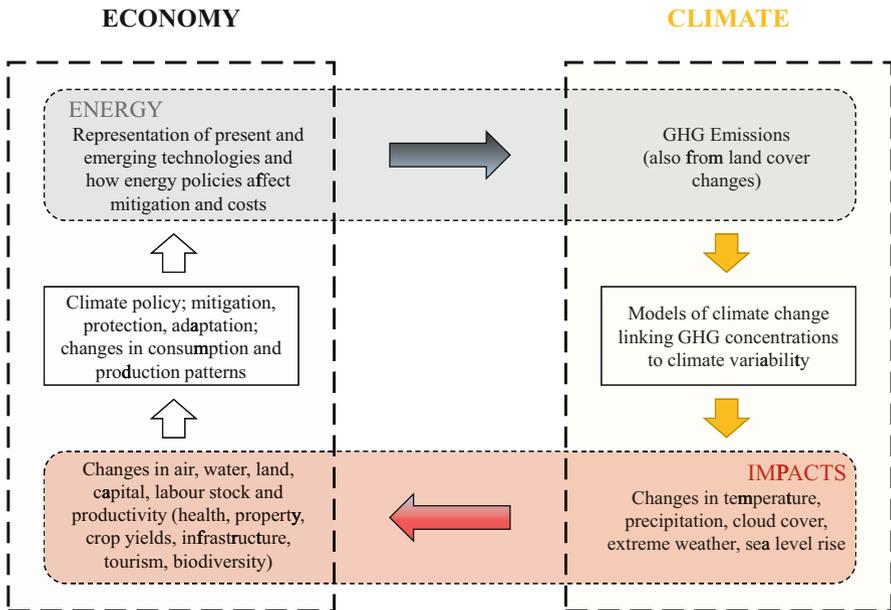


Fig. 1 Climate-economy dynamics with four modules: Economy, climate, impacts, and energy

(or damage function) expresses physical or environmental outcomes as a function of climate variables. For instance, a model might have an agricultural damage function relating variability in temperature, precipitation and cloud cover to crop yields. An economy module may describe the dynamics or growth of an economy, how emissions vary with growth and climate policies and how climate-induced physical and environmental changes might affect parts or all of an economy. The economy model is often augmented with a more detailed energy module that describes the factors determining the uses of different sources of energy and the cost of emission reductions.

The great variety of climate-economy models reflect in part the range of underlying scientific disciplines influencing their development, alternative methodologies and assumptions, as well as the different questions or issues they address. The large and growing number of models and their relative complexity can make it bewildering to distinguish them or understand their unique attributes. There already exist many good reviews of different categories of integrated assessment or climate-economy models in the literature: Fussler (2009) provides general reviews; a special issue of *The Energy Journal* provides more detailed and technical comparisons of IAMs (Weyant 1999); Tol and Fankhauser (1998) and Yohe (1999) review the

modelling and representation of impacts in IAMs; Hitz and Smith (2004) review the way different IAMs deal with the global impacts of climate change as a function of the global mean temperature; and Lecocq and Shalizi (2007) review the literature considering the relationship between growth and climate policy as well as climate change. Other equally thorough reviews can be found in the literature (e.g. Dowlatabadi 1995; Parson and Fisher-Vanden 1997; Kelly and Kolstad 1999; Rana and Morita 2000; Schwanitz 2013; Wei et al. 2015). However, due to the large differences among the models and model categories, these reviews tend to have different perspectives and focus on very specific aspects of the modelling processes, while at the same time using different categorisations.

The objective of this chapter is to look at key characteristics of the available integrated assessment models, while also focusing on their structure and ways of treating uncertainty and technology, in order to help develop a concrete categorisation and form a simple and useful overview of the climate-economy modelling universe. This analysis substantially differs from other often more detailed or narrowly focused “overviews” in that it takes less for granted and aims at providing an initial understanding of generic model structures. This objective is in contrast, for instance, with Ortiz and Markandya (2009), who give short descriptions of many models and their equations, or Stanton et al. (2009) that focus on key assumptions affecting model outcomes or Fussel (2010) that focuses on how adaptation to climate change is incorporated in models. In this respect, this simple and brief overview is meant to complement these other less generic discussions and act as an initial guide to this vast terrain. Section 2 provides an overview of the six classes in which we categorise the existing integrated assessment modelling frameworks. Sections 3–7 present the unique features of each one of the model categories, as well as key characteristics of a large number of representative IAMs. Finally, Sect. 9 concludes the analysis and discusses some key remarks.

It should be noted that there exist in the literature different criteria for considering a modelling framework as an IAM. According to most reviews and from a strict point of view, only models with a close loop between economy and environment effects can be classified as IAMs; thus, most partial equilibrium models cannot be considered alone as IAMs, but can certainly be used as part of an IAM modelling suite. In this research, all models that include separate modules for climate, economy and energy are considered to be IAMs. Exceptions include certain energy system models (Sect. 6) that may not explicitly include a climate module but may rather abstract from climate by including emissions (without climate change or damages), which have also been included in other reviews (e.g. Stanton et al. 2009).

2 Classifying Climate-Economy Models

There exist a large number of various classifications in the literature, which do not fully align with each other or with the one presented in this chapter (e.g. Füssel 2010; Stanton et al. 2009; Ortiz and Markandya 2009; Söderholm 2007). In particular, Füssel (2010) following an older tradition divides them according to the kind of decision analytical frameworks to which they are applied, Stanton et al. (2009) divide them according to model structures and Ortiz and Markandya (2009) classify integrated assessment models by whether all four modules (climate, impacts, economy, energy) are used and how they are combined.

Drawing on these classifications and a detailed literature review of applications, six general modelling structures or approaches are presented. These are distinguished primarily by how the economy is modelled and the way the other three modules (climate, impacts, energy) are integrated. Of course, the nature of these models slightly hinders their consistent classification, given that certain IAMs may inevitably be sorted into more than one class. The six model classes that are presented in the following sections are briefly introduced below:

1. **Optimal growth (or welfare optimisation)** IAMs represent the economy as a single all-encompassing sector. They are designed to determine the climate policy and investment levels that maximise welfare (future against present consumption) over time, by identifying the emission abatement levels for each time step. They tend to be fairly simple, highly aggregated and transparent models that capture the trajectory of an economy and its interaction with climate in a fully integrated fashion, meaning that all modules are represented and endogenously determined.
2. **General equilibrium (or usually referred to as computable general equilibrium—CGE)** models have a more detailed representation of the economy with multiple sectors and often include higher resolution of energy technologies and regional detail. Rather than seeking optimal policies, they consider the impacts of specific policies on economic, social and environmental parameters. The richer representation of the economy comes at a cost in that the growth of the economy is harder to model and its structure more complex.
3. **Partial equilibrium models** provide a detailed analysis of the interaction between environmental impacts and a particular sector of the economy. These are usually used to assess potential climate-induced damages to a specific sector of the economy and are often linked to computable general equilibrium models.
 - (a) **Energy system models** can be considered as a subcategory of partial equilibrium models that provide a detailed account of the energy sector, i.e. energy technologies and their associated costs. These are used, inter alia, to determine the least-cost ways of attaining GHG emission reductions or the costs of alternative climate policies. They are often linked with computable general equilibrium or macroeconomic models in order to add the desired level of insight to top-down approaches.

4. **Macroeconometric models**, like computable general equilibrium models, can be quite detailed in terms of energy technologies and geographic scope and are also used to evaluate alternative climate policies, but they differ in that they do not assume that consumers and producers behave optimally or that markets clear and reach equilibrium in the short term. Instead, they use historical data and econometrically estimated parameters and relations to dynamically and more realistically simulate the behaviour of the economy.
5. **Other integrated assessment models** refer to models that may have little in common except that they do not fit neatly into any of the previous well-known groups. A key departure is that they model the economy in a highly “reduced form” or simply use exogenous growth scenarios (no model at all). Although they significantly differ from one another, they all tend to be more policy-oriented than models of the other five classes.

Table 1 provides an overview of characteristics of the different approaches. The first column labels the overall approach, while the remaining columns describe how each approach varies in the way the four different modules are modelled. The table, acting as a reference point and organising principle, also aligns with the descriptions of the six approaches presented in the remainder of the paper so that the different elements in the boxes can be further explained.

The classification scheme presented in Table 1 is not meant to be exhaustive or comprehensive, and models will often not fit neatly into one of these approaches, while many combine elements of different categories. For instance, Füssel (2010) introduces a separate category referred to as “policy guidance models” and represented by ICLIPS (Toth 2005), which integrates the first four approaches into one model. Furthermore, combining models of different categories towards adding the desired level of detail is not uncommon in the climate policy literature; for example, CGE and macroeconometric models are often combined with energy system models. The connection between the different model categories is an important aspect in the modelling literature, given that certain models focus on specific sectors often neglecting the impacts on the other sectors. At the same time, IAMs that cover the energy, economy and climate are criticised for sacrificing the necessary model granularity for the sake of simplicity. From a modelling perspective, this linkage is complex and understudied in the literature (e.g. Karkatsoulis et al. 2017). Table 2 attempts to provide an overview of the six categories of integrated assessment models with some of their most prominent modelling frameworks, along with a short description and set of indicative applications. Sixty-one modelling frameworks have been reviewed and assessed for the purpose of this study.

Table 1 Key characteristics and classification of climate-economy models

Category	Economy	Impacts	Energy	Climate
Optimal growth models	Neoclassical growth Highly aggregated Tracks long-term trajectory of economy (dynamic) Single production function Single representative agent Policy optimisation Global	Highly aggregated monetary damage function that translates temperature change to loss of GDP All damages in monetary terms	Aggregated energy sector (top-down)	Reduced-form equations linking emissions to temperature
General equilibrium models	Multisectoral (multiple production functions) Single representative agent Optimising behaviour of producers and consumers Global, regional, national, local More difficult to incorporate dynamics	Shocks introduced into production functions, e.g. reduction in crop yields reflected in agricultural production function leading to a shift in supply Shocks can be based on expert judgements or drawn from biophysical or statistical models of impacts	Often detailed description of energy system (multiple energy sources explicitly modelled) Often linked to bottom-up energy system models	Climate scenarios are exogenous and used to drive climate variables and impacts
Partial equilibrium models	Detailed modelling of a single sector, e.g. agriculture Static and dynamic Often combined or linked with other top-down models	(a) Detailed biophysical model of impacts to specific sector relating key climate variables to impacts (b) Statistical analysis leading directly to monetary value of impacts	Little or no representation of energy sector	Exogenous climate scenarios used to drive impacts

(continued)

Table 1 (continued)

Category	Economy	Impacts	Energy	Climate
Energy system models	Can be considered as a subcategory of partial equilibrium models (with some instances including a macro feedback) Often linked to top-down models (making them “hybrid”)	Used to assess costs of reducing emissions; no need to represent impacts	Detailed representation of alternative energy technologies and mitigation opportunities and policies	Focus on emissions rather than climate change
Macroeconometric models	Input-output econometric (multisectoral) Macroeconomy components Simulation: agents not assumed to feature optimising behaviour “Keynesian” Dynamic	Used primarily to evaluate mitigation and adaptation policies rather than evaluate damages arising from climate change	Detailed description of energy system	Exogenous scenarios
Other models	Various simple representations of economy or exogenous scenarios of economic growth	Variety of detailed representations of impacts and damages both physical and monetary	Various aggregated and detailed energy models	Reduced-form equations linking emissions to temperature and other variables

Table 2 Classification of the 61 reviewed models, with a short description and a set of indicative applications

Category	Model	Introduced by	Short description	Indicative applications
Optimal growth models	AD-FAIR	Hof et al. (2009)	A combination of FAIR (analysis of environmental costs of mitigation) and AD-RICE (adaptation cost)	Hof et al. (2012)
	AIM/Dynamic Global	Masui et al. (2006a)	A global dynamic optimisation model for assessing CO ₂ reductions and economic impacts by considering energy saving investments for Japan	Xu and Masui (2009)
	AIM/Enduse	Kainuma et al. (2011)	An optimisation model for Japan, designed to assess energy saving investments	Kainuma et al. (2003)
	CETA-M	Peck and Teisberg (1993)	A growth model representing world economic growth, energy consumption, energy technology choice, global warming and global warming costs	Peck and Teisberg (1995, 1999)
	DEMETER-1 and DEMETER-1CCS	Gerlagh (2006)	A growth model with learning-by-doing for fossil fuels and non-carbon energy	Gerlagh (2007)
	DICE	Nordhaus and Yang (1996)	A modified Ramsey-style optimal economic growth model	Nordhaus (2010)
	DICE-2007	Nordhaus (2008)	An extension of DICE that comprises a modified Ramsey-style optimal economic growth model	Ackerman et al. (2010)
	ENTICE	Popp (2004)	An extension of DICE, including endogenous technological change	Popp (2006a)
	FAIR 2.1	Den Elzen (2005)	A top-down model comprising a socio-economic scenario module, an emission pathway module, a climate model, an abatement costs module, a damage module and a macroeconomic growth module	Hof et al. (2008)

(continued)

Table 2 (continued)

Category	Model	Introduced by	Short description	Indicative applications
General equilibrium models	FEEM-RICE	Buonanno et al. (2003)	A global climate-economy model; extension of RICE and DICE that includes endogenous technological change	Buchner and Carraro (2005)
	GRAPE	Kurosawa et al. (1999)	A growth model consisting of five modules: energy, climate, land use, macroeconomics and environmental impacts	Kurosawa (2004, 2006)
	MERGE	Manne and Richels (2005)	A climate market-oriented, fully integrated assessment model	Kypreos (2007, 2008)
	MIND	Edenhofer et al. (2005b)	An endogenous growth model focusing on the energy sector	Edenhofer et al. (2005a)
	RICE	Nordhaus (1994)	A multiregional extension of DICE	Rosendahl (2004), Schultz and Kasting (1997)
	RICE-99	Nordhaus and Boyer (2000)	A Ramsey-Koopmans single-sector optimal growth model suitably extended to incorporate the interactions between economic activities and climate	Bosetti et al. (2005)
	WITCH	Bosetti et al. (2007)	A top-down Ramsey-type neoclassical optimal growth model with an energy input specification operating as a bottom-up model	Bosetti et al. (2009)
	AIM	Kainuma et al. (1999)	A global CGE model with recursive dynamics that estimates GHG emissions absorption in the Asia-Pacific region and its impact on environment, society and economy	Dai et al. (2011), Fujino et al. (2006)
	AIM/Material	Masui et al. (2003)	A country-based CGE model with recursive dynamics	Masui (2005)
	Dynamic GTAP	Walmsley et al. (2006a)	A dynamic CGE model	Golub et al. (2009)

G-CUBED	McKibbin and Wilcoxon (1999)	A multi-country, multi-sector, intertemporal model applied in the study of GHG policy, trade liberalisation, tax and microeconomic policy	McKibbin et al. (2004)
GEM-E3	Van Regemorter (2005)	A static CGE model evaluating energy, climate and environmental policies.	Nilsson (1999)
GREEN	Burniaux et al. (1992)	A dynamic CGE model studying the economic effects of policies aiming to reduce CO ₂ emissions in Europe	Nicoletti and Oliveira-Martins (1993)
GTAP-E	Burniaux and Truong (2002)	A static CGE model	Kremers et al. (2000)
GTEM	Pant (2007)	A dynamic model of the world economy developed to address global change issues, including those related to climate change policy	Jakeman and Fisher (2006)
ICES	Bosello et al. (2009)	A recursive dynamic, multiregional CGE model of the world economy, extension of GTAP-E	Bosello et al. (2010), Parrado and De Dian (2014)
IGEM	Goettle et al. (2007)	A dynamic model of the US economy describing growth due to capital accumulation, technical change and population change	Goettle and Fawcett (2009)
IMACLIM-R	Crassous et al. (2006)	A multi-sector multi-region recursive CGE model projecting the world economy on a yearly basis	Crassous et al. (2006)
LINKAGE	Van der Mensbrugge (2005)	A global/multi-region, multi-sector, dynamic applied general equilibrium model	Laborde et al. (2016)
MEMO	Bukowski and Kowal (2010)	A large-scale, multi-sector dynamic stochastic general equilibrium model for Poland	

(continued)

Table 2 (continued)

Category	Model	Introduced by	Short description	Indicative applications
Partial equilibrium models	MIRAGE	Behir et al. (2002)	A multi-region, multi-sector CGE model devoted to trade policy analysis	Zaki (2011)
	MIT EPPA	Paltsev et al. (2005)	A recursive-dynamic multiregional CGE model of the world economy that is built on the GTAP dataset and additional data for urban GHGs	Viguier et al. (2003)
	MS-MIRT	Bernstein et al. (1999b)	A multi-sector, multi-region CGE model that has been used to analyse the global impacts of the Kyoto Protocol with emphasis on the international trade aspects of climate policy	Bernstein et al. (1999a)
	SGM 2004	Edmonds et al. (2004)	A CGE model analysing issues related to energy, economy and GHG emissions	Schumacher and Sands (2006)
	WIAGEM	Kemfert (2001)	An economic approach focusing on the international energy market that integrates climate interrelations via temperature changes and sea level variations	Kemfert (2005), Kemfert et al. (2006), Kemfert and Truong (2007)
	WORLDSCAN	Lejour et al. (2006)	A recursive dynamic CGE for long-term issues in international economics	Bollen and Gielen (1999), Bollen (2015)
	GIM	Mendelsohn et al. (2000)	An adaptation partial equilibrium model, predicting the market impacts across climatic scenarios.	Mendelsohn and Williams (2004)
	MiniCAM/GCAM	Edmonds and Reiley (1985)	An IAM of moderate complexity focused on the power and agriculture sectors	Scott et al. (1999)
	TIAM-ECN	Keppo and van der Zwaan (2012)	A version of the TIAM model broadly used for studying energy technology and climate policy scenarios, comprising a global bottom-up energy system model	van der Zwaan et al. (2013)

Energy system models	DNE21+	Sano et al. (2005)	A detailed energy module, rich in terms of energy sources and technologies	Rout et al. (2008), Oda et al. (2009), Wada et al. (2012)
	Calliope	Pfenninger (2015)	A multi-scale energy systems (MUSES) modelling framework, for developing energy system models	Redondo and van Vliet (2015)
	EFOM	Finon (1976)	An energy system model for France	Van der Voort (1982)
	ERIS	Turton and Barreto (2004a)	An energy system model, also covering several non-electric sectors (transportation and thermal needs, and corresponding technologies)	Barreto and Kyreos (2004), Turton and Barreto (2004b)
	GENIE	Mattsson and Wene (1997)	An energy system model that focuses on the implementation of new technologies (primarily photovoltaics and fuel cells) globally	Mattson (2002)
	GET-LFL	Hedenus et al. (2006)	A cost minimisation model, designed to compare the effect of introducing induced technological change in an energy system	Edenhofer et al. (2006)
	MARKAL/TIMES	Fishbone and Abiock (1981)	A model that extensively covers energy production and consumption technologies, as well as linkages to other economic sectors (through exogenous specification of useful energy demand)	Rafaj and Kyreos (2007), Seebregts et al. (2000)
	MEDEE 2	Lapillonne (1978)	A bottom-up demand forecasting model that enables the assessment of the impact of energy efficiency policies at the national level	Lapillonne (1980)
	MESSAGE	Messner (1997)	A cost minimisation, dynamic, linear programming model of the overall energy system	Hainoun et al. (2010), Sullivan et al. (2013)
	NEMS	Gabriel et al. (2001)	A large-scale energy-economy model that computes equilibrium fuel prices and quantities in the US energy sector	Yu (2008)

(continued)

Table 2 (continued)

Category	Model	Introduced by	Short description	Indicative applications
Macroeconomic models	POLES	Criqui et al. (1998)	A world energy-economy partial equilibrium simulation model of the energy sector, modelling from upstream production to final user demand and greenhouse gas emissions	Criqui et al. (1999), Kouvaritakis et al. (2000a, b), Kitous et al. (2010)
	PRIMES	Capros et al. (1998)	An energy model focusing on market mechanisms aimed at explicitly projecting prices influencing the evolution of energy demand and supply as well as technology progress	Capros et al. (2007, 2016)
	WEM	International Energy Agency (2010)	A large-scale mathematical model designed by IEA to replicate how energy markets function.	Kesicki and Yanagisawa (2015)
	E3ME	Barker and Zagame (1995)	A non-CGE energy-environment economy model of the world's economic and energy systems and the environment	Barker (1998, 1999), Barker and Rosendahl (2000), Ščasný et al. (2009)
	E3MG	Barker et al. (2006)	A large-scale macroeconomic simulation model of the global economy with detailed, integrated treatments of energy demand and the consequent atmospheric emissions. It follows E3ME's approach except that at the global level various markets are closed, allowing for imbalances	Barker et al. (2008), Barker and Sereteci (2010), Dagoumas and Barker (2010)
	MDM-E3	Junankar et al. (2007)	A multisectoral dynamic model of the UK for assessing energy-economy-environment issues and other policies	Ekins and Etheridge (2006)
	Oxford Global Macroeconomic and Energy Model	Cooper et al. (1999)	A macroeconomic model designed for assessing the impact of policies towards controlling carbon emissions	Barker and Ekins (2001)

Other models	CIAS	Warren et al. (2008)	A multi-institutional modular IAM for modelling climate change	Warren et al. (2012)
	FUND	Tol (1997)	A non-CGE policy optimisation model that supports policy makers in understanding what an optimal policy looks like, rather than evaluating the consequences of proposed policies	Link and Tol (2004), Ackerman and Munitz (2012)
	ICAM-3	Dowlatabadi (1998)	A simulation model designed to assess the mitigation cost regarding technical change	Dowlatabadi (2000)
	IGSM2	Sokolov et al. (2005)	An economic model for analysis of GHG and aerosol precursor emissions and mitigation proposals	Reilly et al. (2006)
	IMAGE 2.4	Bouwman et al. (2006)	A policy evaluation model	Stehfest et al. (2009)
	PAGE2002	Hope (2006)	A version of the PAGE model that incorporates the five IPCC reasons for concern	Hope (2008, 2009)
	PAGE09	Hope (2011)	An updated version of PAGE2002 that takes into account IPCC 4th Assessment Report	Hope (2013)

3 Optimal Growth Models

Optimal growth or welfare optimisation IAMs tend to be more transparent because they are relatively simple, compared to models of other categories with more complex structures. They have solid microeconomic foundations and focus explicitly on the development of the economy over time. Social welfare is often defined as the utility of a representative agent, and the overall objective is to maximise aggregated welfare over time. In neoclassical economic growth models, economies make investments in capital, education and technologies. These enhance future consumption by sacrificing some present consumption, the objective being to find the right balance between present consumption and investment in future consumption so as to maximise overall welfare. IAMs of this class extend the neoclassical growth models by including the “natural capital” of the climate system as an additional kind of capital (Nordhaus 2014). Increased emissions of GHGs effectively deplete natural capital, while abatement investments augment it. In addition to standard investments, natural capital used today enhances present consumption versus expending resources in order to protect the climate system, or to avoid damage from climate change, for future welfare. In terms of climate policy, these models compare alternative paths of emissions over time (abatement) in order to find the policy that maximises overall social welfare.

Table 3 presents a set of key models falling under this class, along with information regarding the perspective of the model, the number of regions and forecasting period it can cover and the damage function by means of which the damages are translated into monetary terms. The model perspective describes the overall approach of the modelling framework: a top-down approach looks at the system under examination as a whole and uses reduced form behavioural relationships with econometrical validation, while bottom-up approaches are developed from an engineering perspective and start from the sector of interest in detail before expanding the focus onto the whole system. Other settings are more flexible and can be described as being developed from a hybrid perspective, i.e. combine different levels of detail for specific sectors or the system—a particular class of hybrid models are economic engineering models, which combine microeconomic foundations of behaviour with explicit engineering and technology details (see, e.g. Sect. 6).

Most of the modelling frameworks in this category are top-down approaches, with the exception of AIM/Enduse, which can also be considered as a non-integrated assessment model, since no economic module is included. CETA-M, WITCH and MERGE feature a hybrid model perspective, while DEMETER-1(CCS) is a classic top-down model incorporating insights from the bottom-up literature regarding learning-by-doing effects (Ortiz and Markandya 2009).

The DICE (dynamic integrated climate economy) global model (Nordhaus and Yang 1996) is selected in this study as a representative model of this category. In DICE, countries are aggregated into a single level of output, capital stock, technology and emissions (in a regional setting, RICE is a multi-region version of DICE). The social welfare function represents the world’s well-defined set of preferences

Table 3 Overview of optimal growth integrated assessment models

Model	Model perspective	Regions	Forecasting period	Damages		Source
				Function		
AD-FAIR	Top-down	Regional (17)	2010–2100	$\frac{GDPr,t}{Yr,t} = a1 \cdot r\Delta Tt + a2 \cdot r\Delta Tt^{a3 \cdot r}$ where $a1, a2, a3$ are parameters, t is period, r is region, ΔT is temperature change, Y is GDP	Hof (2010)	
AIM/ Dynamic Global	Top-down	Global (6)	1995–2100	Sectoral models		
AIM/ Enduse	Bottom-up	National (Japan)	2005–2050	No economic module incorporated		
CETA-M	Hybrid	Global (OECD, ROW)	2000–2150	$Ct = aLIT^\lambda$ T is temp rice above pre-industrial age, λ is parameter, t is period, C is annual warming cost, a is scaling constant	Peck and Teisberg (1993)	
DEMETER-1 and DEMETER-ICCS	Top-down	Global	150 years	No damage treatment		Ortiz and Markandya (2009)
DICE	Top-down	Global	1985–2105	$R = \frac{1}{1 + 0.00284 \cdot T^2}$ where T is global temperature	Ackerman and Stanton (2012)	
DICE-2007	Top-down	Regional (17)	Until 2200	$\frac{D(t)}{Y} = 1 - \frac{1}{1 + \eta \cdot T^B}$ where $\frac{D(t)}{Y}$ is fractional reduction of production, $B = 2$, $\eta = \eta$ non-catastrophic + η catastrophic = 28% T is global warming relative to pre-industrial	Kopp and Mignone (2012)	

(continued)

Table 3 (continued)

Model	Model perspective	Regions	Forecasting period	Damages		Source
				Function		
ENTICE	Top-down	Global (6)	2000–2300	$\Omega(t) = \frac{1}{1 + a1 + Tt + a2Tt^2}$ <p>where t is period, T is global temperature, $a1, a2$ are parameters</p>	Popp (2006b)	
FAIR2.1	Top-down	National (Japan)	2005–2250	$Yt = A \cdot K^\alpha \cdot L^{(1-\alpha)}, Kt + 1 = Kt - \eta Kt + It$ <p>where Y : GDP, K : capital, L : labor, a : capital elasticity of production, I : investment, η : depreciation, t : period</p>	Hof et al. (2008)	
FEEM-RICE	Top-down	Global (OECD, ROW)	Until 2200	$\Omega(n, t) = \frac{1 - b1, n \cdot \mu(n, t)^{b2, n}}{1 + \theta1 \frac{1}{\exp(\text{SAD}(n, t))} \cdot \frac{T(t)^{\theta2}}{2.5}}$ <p>where T is global temp. $\theta1, \theta2, b1, b2, n$ are Nordhaus coefficients, n is region, t is time, SAD is stock of capital devoted to adaptation, μ is abatement cost</p>	Bosello (2010)	
GRAPE	Top-down	Global	2000–2100	$R = \frac{1}{1 + 0.00284 \cdot T^2}$ <p>where T is global temperature</p>	Koji et al. (2009)	
MERGE	Hybrid	Global	2000–2150	<p>Market Damages :</p> $Dt, r = d1, r \cdot \Delta ATt, r^{d2, n} \cdot \text{GDP}t, r$ <p>where ΔAT is variation of temperature, t is period, r is region</p> <p>Non-market damages :</p> $\text{WTP}t, r = \frac{d3, r \cdot \Delta ATt, r^{d4, r}}{1 + 100 \exp\left(\frac{-0.23 \text{GDP}t, r}{\text{Pop}t, r}\right)}$ <p>where Pop is capital, and $d1, d2, d3, d4$ are damage parameters</p>	Manne et al. (1995)	

MIND	Top-down	Global	1995–2300	No damage treatment	Ortiz and Markandya (2009)
RICE-1994	Top-down	Global	1990–2200	$\Omega_i(t) = \frac{1 - b_1 \cdot i \cdot \mu i(t)^{b_2}}{1 + \theta_1 \cdot iT(t)^{\theta_2}}$ <p>where T is temperature, t is period, i is region, μ is rate of emissions reduction, b_1, b_2 are parameters of emissions reduction cost θ_1, θ_2 are parameters of climate damage function</p>	Nordhaus and Yang (1996)
RICE-99	Top-down	Regional (7)	1995–2105	$\Omega_i(t) = \frac{1 - b_1 \cdot \mu(t)^2}{1 + D(t)}, D(t) = \theta_1 T(t) + \theta_2 T(t)^2$ <p>T is global temp, μ is control rate, θ_1, θ_2 parameters of damage function b is parameter of emissions reduction cost function, $t = 1990, 2000, \dots$</p>	Nordhaus (2002)
WITCH	Hybrid	Regional (10)	2000–2150	$\Omega_t = \frac{1}{1 + \theta_1 \cdot n \cdot Tt + \theta_2 \cdot n \cdot Tt^2}$ <p>where T is temperature, t is period, n is region, θ_1, n, θ_2, n are damage function parameters</p>	Bosetti et al. (2007)

and accordingly ranks different consumption paths. Welfare is increasing in per capita consumption for each generation but with diminishing marginal utility of consumption. The more you consume (or the wealthier you are), the less valuable an additional unit of consumption is. If we expect future generations to be wealthier, then additional consumption for them is less valuable than it is for us. Two central normative parameters determine the relative importance given to different generations. The pure rate of time preferences is a subjective weighting of consumption at different times, and a positive value means that immediate consumption is valued more than future consumption. Higher values increase the bias towards present consumption. The elasticity of the marginal utility of consumption is a measure of how many additional units of consumption fall in value in terms of utility. For a given growth in consumption over time, higher elasticity means that an additional unit of consumption is more valuable today than in the future.

The overall savings rate for physical capital and the rate of control of emissions of greenhouse gases are the two key decision variables for the economy. A single commodity can be either consumed or invested. Consumption viewed broadly includes food and shelter as well as environmental amenities and services. The production of output is represented by a Cobb-Douglas production function in capital, labour and energy. Energy can come from carbon-based fuels or non-carbon-based technologies. Technological change can come from economy-wide technological change or carbon-saving technological change.

The key feature that turns the neoclassical growth model into a fully integrated assessment model is the linking of certain geophysical relationships affecting climate change to the economy: the carbon cycle, a radiative forcing equation, climate change equations and a climate-damage relationship. In the DICE-2007 model, industrial CO₂ emissions constitute the only GHG that can be controlled and vary with total output, a time-varying emissions-output ratio and a rate of control of emissions. The cost of tougher climate policies will be reflected in reductions in output. A radiative forcing equation calculates the impact of GHG accumulation on the radiation balance of the globe. The climate equations that draw from general circulation models calculate the mean surface temperature of the globe and the average temperature of the deep oceans. The climate-damage relationship translates climate change into economic damages by drawing on estimates of economic impacts from other work.

Regarding technology, all optimal growth models among those reviewed assume exogenous (induced) technological change (ITC), while most also incorporate parameters that are endogenously approached (endogenous technological change—ETC); the only exception appears to be the WITCH model, in which technology is exclusively changed endogenously (Table 4). In contrast to DICE, in the latest DICE-2007 model (Nordhaus 2008), both forms of technological change are exogenous, which can be perceived as a serious limitation, especially as changes in carbon prices would be expected to induce carbon-saving technological change.

As suggested in Table 4, uncertainty in optimal growth models is usually treated deterministically, in their original design; only DICE applications have treated uncertainty in a probabilistic manner, by means of Monte Carlo analysis

Table 4 Technological change and uncertainty treatment in optimal growth models

Model	Technological change		Uncertainty treatment		Stochastic	Uncertainty factors
	Endogenous	Exogenous	Deterministic	Sensitivity analysis		
AD-FAIR		✓	Sensitivity analysis			Future damage costs, adaptation costs (Hof et al. 2009, 2012)
AIM/Dynamic Global	✓	✓	Scenario analysis; sensitivity analysis			Capital depreciation rate (Xu and Masui 2009), energy efficiency improvements (Masui et al. 2006a)
AIM/Enduse		✓	Scenario analysis; sensitivity analysis			Demographic trends, economic growth rate, industrial structure and goods shipments, required office space, transportation (Kainuma et al. 2000), availability, performance and cost of new technologies (Akashi et al. 2012)
CETA-M		✓	Scenario analysis; sensitivity analysis			Autonomous energy efficiency improvement rate, fossil fuel resources, electric and non-electric backstop costs, warming per emissions, adaptation costs, exogenous emissions, carbon cycle, labour growth rate, discount rate (Peck and Teisberg 1993)
DEMETER-1 and DEMETER-1CCS	✓	✓	Scenario analysis; sensitivity analysis			CCS costs (Gerlagh and van der Zwaan 2006)
DICE	✓	✓	Sensitivity analysis		Monte Carlo analysis	All model parameters (e.g. rate of capital depreciation, elasticity of output, rate of CO ₂ transfer, pure rate of social time preference, etc.) (Nordhaus and Yang 1996); climate sensitivity (Ackerman et al. 2010)
DICE-2007		✓			Monte Carlo analysis	Total factor of productivity, rate of decarbonisation, population growth, cost of backstop technology, damage-output coefficient, atmospheric retention fraction of carbon dioxide,

(continued)

Table 4 (continued)

Model	Technological change		Uncertainty treatment		Stochastic	Uncertainty factors
	Endogenous	Exogenous	Deterministic			
ENTICE	✓	✓	Scenario analysis; sensitivity analysis			temperature sensitivity coefficient, and total availability of fossil fuels (Nordhaus 2007) Opportunity cost of R&D, deviation between the private and social rates of return to R&D, decay rate of knowledge, return to energy R&D, elasticity of R&D, exogenous reduction of carbon intensity (Popp 2004)
FAIR2.1		✓	Scenario analysis			Climate sensitivity, abatement costs, damage costs, discount rate, time horizon (Hof et al. 2008)
FEEM-RICE	✓	✓	Sensitivity analysis			Discount rate, climate change damage (Bosello 2010)
GRAPE		✓	Scenario analysis			CCS (carbon transport and storage) costs (Kurosawa 2004)
MERGE		✓	Scenario analysis (2005 version); sensitivity analysis		Monte Carlo analysis (2008 version); sensitivity analysis	Global efficiency price of carbon, abatement strategy (Manne and Richels 2005); climate sensitivity, carbon value (Kypraios 2008)
MIND	✓	✓	Sensitivity analysis			Resource costs, labour R&D, energy R&D, learning rate, resource extraction learning rate (Edenhofer et al. 2005b)
RICE-1994		✓	Sensitivity analysis			All model parameters (e.g. rate of capital depreciation, elasticity of output, rate of CO ₂ transfer, pure rate of social time preference, etc.) (Nordhaus and Yang 1996)
RICE-99		✓	Scenario analysis			Population growth, total factor productivity, energy efficiency, changes in land use, climate sensitivity, discount rate (Von Below and Persson 2008)
WITCH	✓		Scenario analysis (2005 version)		Monte Carlo analysis (2008 version)	Abatement costs (Bosetti et al. 2008)

(e.g. Nordhaus 2007; Ackerman et al. 2010). Furthermore, the MERGE and WITCH integrated assessment models were upgraded in their 2008 versions so as to include Monte Carlo analysis in treating uncertainty.

4 Computable General Equilibrium Models

This section draws heavily on Wing's lucid presentation of the basic structure of all computable general equilibrium models used for economy-environment interactions (Wing 2011). CGE models are an algebraic representation of the intricate functioning of a market economy and are based on the core abstract theoretical foundation of how a decentralised price system works. Demand and supply for goods arise from consumers maximising utility and producers maximising profits, with prices bringing about equilibrium in the markets. What makes them "computable" models is the use of economic data to derive numerical parameters that will simulate the real world when solved for equilibrium prices, demand and supply levels of goods. National Accounts for a specific year provide the requisite information on expenditures for goods and services by production sectors and households, as well as the division of factors of production across producers. Data is also required to determine the price elasticities of demands and supplies and factor substitution. This data is usually derived from other empirical work analysing how the behaviour of agents responds to price changes. With the use of National Accounts and elasticity data, the parameters of CGE equations are "calibrated" so that the equilibrium solution of the numerical model precisely reproduces the data of a real economy for a given year.

The general way that CGE models are used for policy analysis is to change one or more of the exogenous parameters of the economy and compute the new equilibrium. Comparing the new counterfactual equilibrium to the initial equilibrium vectors of prices and activity levels as well as the level of utility of the representative household provides insights about the effect of a "shock" on the economy.

By modelling the linkages between the different sectors of an economy, CGE models are able to capture not only the direct impacts of a policy on one sector of the economy but to trace its full (or general equilibrium) impact on the interdependent sectors of an economy and ultimately the change in consumption (or utility) of the representative agent, which is a measure of the welfare impact. A carbon tax will not just increase the cost of certain forms of energy but will also affect the demand and supply of other goods. This is one of the main advantages of these models relative to partial equilibrium models that focus on a single sector or other models that do not have a detailed multi-sector representation of the economy. For example, neoclassical growth models that model the economy as a single sector cannot capture these general equilibrium effects, despite focusing on a broader understanding of long-term dynamics. An overview of the reviewed CGE models can be found in Table 5.

CGE models have traditionally focused on evaluating the costs of emission reductions, alternative mitigation policies and the damages resulting from climate change. Increasing attention is also given to considering the costs and benefits of

Table 5 Overview of computable general equilibrium models

Model	Model perspective	Regions	Forecasting period
AIM	Top-down	Regional (21)	1990–2100
AIM/Material	Top-down	Japan	1995–2010
Dynamic GTAP	Top-down	Global	1997–2025
G-CUBED	Top-down	Regional (8)	2000–2100
GEM-E3	Top-down	Regional (Europe)	1996–2020
GREEN	Top-down	Global	1985–2050
GTAP-E	Top-down	Regional (5)	
GTEM	Top-down	Global	1997–2100
ICES	Top-down	Regional (14)	2001–2050
IGEM	Top-down	Regional (USA)	2000–2060
IMACLIM-R	Top-down	Regional (5)	1997–2100
LINKAGE	Top-down	Global	2004–2080
MEMO	Bottom-up	National	2010–2030
MIRAGE	Top-down	Regional	2004–2020
MIT EPPA	Top-down	Regional (16)	2000–2100
MS-MRT	Hybrid	Regional (10)	2000–2030
SGM 2004	Hybrid	Global (14)	2000–2050
WIAGEM	Top-down	Regional (25)	2000–2050
WORLDSCAN	Top-down	Regional (16)	2000–2050

adaptation. A standard exercise is to examine the effect that a carbon tax will have on an economy's output and emissions of greenhouse gases. A multi-region model with international trade could examine how carbon tax policies would perform if different countries apply different tax rates (Elliott et al. 2010). A typical way of capturing the impacts of climate change on an economy in a CGE model is to model the shocks through several possible channels. Rising temperatures can lead to changes in consumer expenditure patterns such as an increase in demand for air conditioning in the summer or a drop in demand for heating in the winter. By introducing a shock parameter into the representative agent's expenditure function, this influence can be captured. To the extent that climate change reduces the productivity of space conditioning, the shock parameter rises, leading to increases in expenditure required for a given level of space conditioning and thus ultimately negatively impacting the households' welfare. In a similar fashion, shock parameters can be introduced to account for changes in the productivity of primary factors in various industries. If climate change reduces (or increases) the yield of certain crops, then a shock parameter can be changed to capture the reduced productivity in the agricultural sector. Comparing a benchmark equilibrium where the shock parameter has a unit value with a new equilibrium resulting from changed parameter values on agricultural productivity will give a measure of the welfare loss from this impact of climate change. Shock parameters can also be introduced to capture reductions in the aggregate endowments of capital and labour such as those arising from damage to property or from increased morbidity or mortality. By appropriately incorporating a

full set of possible climate change impacts through relevant shock parameters, the computable general equilibrium model is able to tally the loss of welfare to the representative agent resulting from the several productivity shocks. This method, however, does not capture impacts that do not register in markets such as loss in biodiversity or an increase in risk of morbidity and mortality.

Technological change and uncertainty treatment are presented in Table 6. In this domain, CGEs appear similar to optimal growth models, in that they mostly feature induced technological change, although GEM-E3, IGEM, IMACLIM-R and MIT EPPA also have technological aspects endogenously determined, and in that they all treat uncertainty by means of scenario or deterministic sensitivity analyses. The only exception in CGE modelling applications in the literature appears to be the MIT EPPA model, in which anthropogenic emissions of greenhouse gases and precursors were sampled with Monte Carlo analysis (Webster et al. 2002, 2003).

Since the economy in CGE models is always at an optimum, any restrictions on GHGs necessarily lead to costs or losses in output. No regrets or double dividends are possible in these models; this contrasts with some macroeconomic models discussed in Sect. 7. DeCanio (2003) carries out a detailed, fundamental critique on the underlying theoretical basis of CGE models.

5 Partial Equilibrium Models

Partial equilibrium analysis differs from general equilibrium modelling primarily by focusing on a specific market or sector and assuming that prices (or conditions) in the rest of the economy remain constant or unchanged. It is usually justified theoretically when the changes being considered affect primarily one market and are expected to have a relatively small impact on the rest of the economy. Partial equilibrium analysis is used extensively to estimate the impacts of climate change in different sectors of the economy. Although partial equilibrium analysis is unable to capture the broader implications that climate impacts or mitigation will have as sector changes reverberate through all economic sectors, it has the advantage of providing a more detailed understanding compared to a general equilibrium appraisal, which can be very useful in designing policy.

One of the early applications of partial equilibrium analysis to assess the impacts of climate change was on the agricultural sector. Two distinct ways to measure the impact of climate change on agriculture have emerged: a statistical approach and a biophysical approach. Mendelsohn et al. (1999) used the biophysical approach to estimate damages to the agricultural sector in the USA: simulation models were used to predict changes in yield from crop (damage function), and then these provided the inputs for a spatial partial equilibrium model of the US agricultural sector. Much like their general equilibrium counterparts, this shift in the parameter of a production function that would result from climate change brings about a new equilibrium, and the difference in welfare is a measure of the economic damage caused.

Table 6 Technological change and uncertainty treatment in CGE models

Model	Technological change		Uncertainty treatment		Uncertainty factors
	Endogenous	Exogenous	Deterministic	Stochastic	
AIM		✓	Scenario analysis		Population growth, economic growth, climate sensitivity (Matsuoka et al. 1995); industry production structure, product composition, technology popularising rate external policy environment aspects (Wen et al. 2014)
AIM/Material		✓	Scenario analysis		Labour productivity, non-energy material input reduction, energy efficiency improvement, energy mix (Masui et al. 2006b)
Dynamic GTAP		✓	Scenario analysis		Policy mix (Walmsley et al. 2006b); total factor productivity (Ianchovichina et al. 2001); demographic trends (Tyers and Shi 2012)
G-CUBED		✓	Scenario analysis		Emission permit allocation regimes (McKibbin and Wilcoxon 2009)
GEM-E3	✓		Scenario analysis		Policy mix (Nilsson 1999)
GREEN		✓	Scenario analysis		Market structure (Burniaux 1998)
GTAP-E		✓	Scenario analysis		Emission permit allocation regimes (Nijkamp et al. 2005)
GTEM		✓	Scenario analysis		Supply of labour, land growth, natural resources, population growth (Pant et al. 2007); emission trading regimes, economic growth, consumption growth (Tulpulé et al. 1998)
ICES		✓	Scenario analysis		Temperature increase (Bosello et al. 2009); carbon credit allocation regime (Bosello et al. 2010)

IGEM	✓	✓	Scenario analysis	Carbon offset mechanism structure (Fawcett 2011)
IMACLIM-R	✓		Scenario analysis	Economic growth, technological change, policy mix (Waisman et al. 2012)
LINKAGE		✓	Scenario analysis	Agricultural productivity growth (Zhai and Zhuang 2012)
MEMO		✓	Scenario analysis; sensitivity analysis	Policy mix, technological mix (Bukowski and Kowal 2010)
MIRAGE		✓	Scenario analysis	Market structure (Behir et al. 2003)
MIT EPPA	✓	✓	Scenario analysis	Burden sharing scheme (Viguier et al. 2003); anthropogenic emissions for all GHGs and aerosol and GHG precursors (Webster et al. 2002, 2003)
MS-MRT		✓	Scenario analysis	Emissions trading system structure (Bernstein et al. 1999b)
SGM 2004		✓	Scenario analysis; sensitivity analysis	Technology readiness, carbon prices, interest rates (Schumacher and Sands 2006)
WIAGEM		✓	Scenario analysis; sensitivity analysis	Emission stabilisation levels (Kemfert and Truong 2007); radiative forcing constraints, set of GHGs, emission abatement elasticities (Kemfert et al. 2006)
WORLDSCAN		✓	Scenario analysis	Emission stabilisation levels (Bollen and Green 1999)

Producers' costs are a function of the outputs of the goods they produce, factor prices and exogenous environmental inputs like climate, soil quality, air quality and water quality. In the statistical approach, land is separated from other production inputs and considered to be heterogeneous with different environmental characteristics. Perfect competition for land is assumed which implies that entry and exit will drive pure profits to zero. In this case land value should be equal to the net revenue from the land, which is linked to the value of land. This "Ricardian" model allows one to measure the impact of a change in an environmental variable through the impact on the value of land. A change in an environmental factor that damages production will lead to a fall in the stream of future of land rents and in the value of land. If prices for all markets (except that of land) are assumed constant, the value of the environment change is captured by the change in aggregate land values. In order to discern the impact of climate variation (as well as mean temperature) on property values, Mendelsohn et al. (1999) used cross-sectional data on aggregate land values in different counties along with 12 climatic variables (of temperature and precipitation). They then regressed aggregate farm values on climate, soil and economic variables in order to determine the marginal impact of each climate variable. Essentially, differences in temperature and weather patterns at a point in time across various regions were used to project climate change impacts in the future.

Both biophysical and statistical partial equilibrium approaches have been used to estimate impacts of climate change across multiple sectors of an economy. With consistent assumptions across sectoral analyses, these are often added up to provide a value of total impact to an economy. This total value does not capture non-market impacts such as health and biodiversity.

The idea of drawing on the literature of biophysical models to find the physical climate impacts for different sectors and then translate these into monetary values by various methods (first order calculations, partial equilibrium models, and guesstimates) and add them up to find a total monetary value of "damages" from climate change is also known as the "enumerative approach". This is probably one of the easiest methods to grasp conceptually as the move from the physical to the monetary valuation is more transparent. Estimates of "physical effects" of climate change on specific sectors of the economy or environmental services are obtained from natural science work (climate models, impact models and laboratory experiments). Economic valuation methods are then used to place a monetary value on the physical impact, and this can either provide an estimate of damage to a specific sector like agriculture, or the values of damages to the different sectors (tourism, agriculture, forestry, biodiversity, etc.) can be added up to give an estimate of the total damages of climate change to a region. For instance, engineering estimates can be used to find the physical effect that a rise in sea level has on coastal protection and loss of land. Economic estimates of the cost of coastal protection and the value of lost land or land protection follow. For goods that are not traded in markets, like climate impacts to health and biodiversity, other economic techniques are needed to estimate monetary values. Physical loss to health could be translated into monetary terms by considering medical expenses, productivity loss or citizens' willingness to pay to avoid risk of health damages (Tol 2010).

Theory does not suggest that adding up the separate economic sectoral impacts will lead to the same result as evaluating total climate change impacts with a computable general equilibrium or macroeconomic model that incorporate all market interactions. A particularly stark example of the importance of capturing market interactions can be found in the literature on what is known as the “rebound effect” (Sorrell 2009). Improvement in energy efficiency might be expected to directly lead to reductions in energy consumption and GHG emissions, and many policies to improve energy efficiency have that aim. An analysis that looks just at the immediate impact of energy efficiency or savings policy might lead to that conclusion. However, empirical and theoretical literature show that there can often be a rebound effect such that any gains in energy efficiency are countered by increases in energy consumption. This could happen because the improved energy efficiency brings about a fall in the price of energy leading to increased use of energy or the development of new energy-using products.

The more detailed analysis and quantification of damage functions that are part of the partial equilibrium studies or enumerative approaches have also been used as inputs into general equilibrium models; for example, Jorgenson et al. (2004) use sectoral damage functions as inputs into their Intertemporal General Equilibrium Model (IGEM). This distinguished their approach from many computable general equilibrium models that did not rely on damage functions derived from more detailed empirical sectoral studies. A damage function is used to describe how unit costs or the supply of input factors changes as a result of climate variation. For instance, for the sectors of crop agriculture, forestry, energy and water, a damage function is used in order to relate the percentage change in unit production costs to changes in temperature and precipitation. The difference between the unit price of producing a given quantity before and after the impact of climate change is used in the model to reflect the change in productivity or inputs required to produce the same amount of a good. This productivity change is incorporated in the relevant sector of the CGE to model the full economic implications of the climate impacts.

The three partial equilibrium models reviewed are presented in Table 7. It is obvious that technological change differs across the three models, all of which are of global coverage. Only the GCAM model (formerly known as MiniCAM) features both endogenous and induced technological progress as well as characteristics of both bottom-up and top-down approaches (Urban et al. 2007), and, contrary to GIM and TIAM-ECN, there have been applications featuring uncertain parameters treated stochastically by means of Monte Carlo analysis (Scott et al. 1999).

One of the advantages of a sectoral approach is that it allows a much more detailed understanding of the various climate impacts and a more refined estimation of specific impacts on parts of the economy. One recent study known as PESETA (Ciscar et al. 2009) combined sectoral and computable general equilibrium models to produce a Europe-wide analysis of climate impacts for five categories: agriculture, tourism, river floods, coastal systems and health. The study pointed to the disadvantages of other regional integrated assessment studies that rely on reduced-form damage functions relating global temperature to GDP (as most wealth maximising IAMs do). Specifically, these reduced-form damage functions are often based on

Table 7 Overview of partial equilibrium models, including uncertainty treatment and technological change

Model	GIM	MiniCAM/GCAM	TIAM-ECN
Model perspective	Top-down	Hybrid	Bottom-up
Regions	Global (178)	Global (14)	Global (36)
Forecasting period	1990–2100	1990–2100	2010–2100
Technological change	Endogenous	Endogenous; exogenous	Exogenous
Uncertainty treatment	Deterministic (scenario analysis)	Deterministic (scenario analysis); stochastic (Monte Carlo analysis)	Deterministic (scenario analysis)
Uncertainty factors	Climate prediction models (Mendelsohn and Williams 2004)	Policy mix, emissions, atmospheric concentration, radiative forcing, global mean temperature and climate sensitivity, damages for the no intervention case, cost of stabilising emissions, cost of stabilising the atmosphere, cost of stabilising the climate (Scott et al. 1999)	Radiative forcing levels (van der Zwaan et al. 2013)

literature that draws on different and possibly inconsistent climate scenarios; only average temperature and precipitation are used rather than a fuller set of climate variables at an appropriate time-space resolution, resulting in estimates of impacts not having a detailed enough geographical resolution. In contrast, PESETA followed an enumerative (bottom-up) approach, which means that the impact assessment was based on much more detailed sectoral models deriving from the regions under study. In order to meaningfully add these impacts up, common climate scenarios were used at a high time-space resolution. Finally, the impacts derived from each sector were fed into a computable general equilibrium model (GEM-E3) allowing for the assessment of impacts, after market interactions had been incorporated. Another recent example of a national climate change assessment combining a sectoral approach with a top-down CGE can be found in the Garnaut Climate Change Review (Garnaut 2008).

6 Energy System Models

While much of the discussion on partial equilibrium models (Sect. 5) focused on ways of estimating damages that climate change may cause, energy system models focus on the key sector determining GHG emissions and costs arising from emission reduction policies. Numerous models have been developed over the years to provide energy policy guidance and that have evolved into integrated assessment models or

components of IAMs. The analysis of energy and environmental policy often demands a level of technological explicitness and detail that goes beyond macro-economic models that do not differentiate technology stocks. A class of technology-oriented models known as “bottom-up” models emerged in the 1970s (following the first oil crisis) and are still being developed, for the purpose of addressing this need for detail. While these were developed for energy resource planning purposes and began with simple, single-sector accounting tools, they soon evolved into complex and dynamic optimisation and simulation frameworks for energy and climate policy appraisal at local, national or international levels (Greening and Bataille 2009). As Mundaca et al. (2010) note, these models are disaggregated representations of the energy-economy system, entailing detailed characterisations of existing and new energy technologies, and can simulate alternative technological pathways. Besides considering least-cost means of achieving emission targets, these models are employed towards identifying a number of climate-energy issues, including best technology opportunities, costs of alternative mitigation policies and the potential for greater energy efficiency.

Energy system models can broadly be classified as optimisation models or simulation models. Optimisation models use information on costs and constraints of technology characteristics to identify the “best”, “least-cost” or “optimal” technology. The consumer is assumed to be rational, and energy supplies are allocated to energy demands, based on minimum lifecycle technology costs. By incorporating a constraint on emissions, an optimisation model can estimate the least costs of achieving a target. Simulation models are designed to capture technological and economic dynamics as realistically as possible. Rather than seeking to find a least-cost solution, they model the most probable responses to policy shocks. Producers and consumers may carry out production and consumption activities with different objectives in contrast to optimisation models that usually operate from the perspective of a single optimising decision-maker. There are many simulation models of various degrees of sophistication. A sequential iterative simulation process is used to find an equilibrium set of prices and demands. A policy application affects prices, and the iterations continue until a new equilibrium is found. Outcomes are very sensitive to the dynamics and technologies assumed. A simulation, for instance, of a GHG policy will lead to very different results if carbon capture and storage or other backstop technologies are included. Table 8 presents an overview of the reviewed energy system models, along with their system, geographical and time coverage, mathematical structure and perspective.

The technological explicitness and detail of energy system models allow them to consider such issues as how policies can promote technology commercialisation and diffusion, but they have been criticised for lacking microeconomic (or behavioural) realism and “macroeconomic completeness” (or feedbacks). In terms of behavioural realism, they have been criticised for being too optimistic on the profitability of attaining energy efficiency from the diffusion of low-emission or inexpensive technologies. Part of the problem is that bottom-up models focus mostly on the financial costs while not taking into account such key factors as greater risks, intangible costs and longer payback periods associated with investments in energy

efficiency. For instance, two light bulbs that may appear to provide the same service in terms of lumens may differ in risk of premature failure, payback period, shape, hue of light or time it takes for a bulb to reach full intensity; similarly, public transit and single-occupancy vehicles may provide the same personal transportation service, but evidence suggests that some consumers perceive public transportation as being of lower convenience, status and comfort level. By incorporating more parameters to gauge for consumers preferences, like time preferences or perception of risks, models will be better able to explain and predict the potential uptake and diffusion of new technologies. Mundaca et al. (2010) review models that attempt to capture more of this behavioural realism for the analysis of energy efficiency policies.

Being essentially partial equilibrium models focusing on energy consumption, energy system models tend to find relatively low mitigation costs because they only consider the impact of emission reduction strategies on energy system costs usually ignoring feedback loops and interactions with other sectors of the economy; exceptions of such models including feedback loops, however, can be found in the literature (e.g. Karkatsoulis et al. 2017). For instance, these models assume that investments within the energy sector can be funded at a constant rate of interest. An ambitious climate policy, however, would lead to a depreciation of capital stocks in certain sectors and accordingly change the return on investment in the energy sector as well as a concomitant reallocation of investments across sectors. These investment dynamics are a critical determinant of macroeconomic costs missed by the partial equilibrium analysis. For the same reason, most energy system models tend to neglect the potentially significant rebound effects and crowding-out implications of investments (Edenhofer et al. 2006).

As Table 8 suggests, all energy system models are bottom-up; exceptions include hybrid models (Greening and Bataille 2009) that also feature characteristics of top-down approaches, like MESSAGE and WEM (Urban et al. 2007), and economic engineering models in particular, combining microeconomic foundations of behaviour with technology details (such as DNE21+, NEMS, POLES and PRIMES). In a broader perspective, there are numerous ways that bottom-up models have added macroeconomic components, whether these derive from optimal growth models, macroeconomic models or computable general equilibrium models. Because of the technological explicitness of bottom-up models, the top-down feedbacks have focused on direct adjustment effects on the demand for energy-using goods and services in response to changes in the cost of delivery, but do not capture the secondary macroeconomic effects like change to wages, cost of capital, exchange rates and government budgets resulting from energy price changes. When governmental energy policies are moderate in scope, they are unlikely to have substantial macroeconomic implications, but as policies become more ambitious—as would be required for a rapid reduction in GHG emissions or a big shift towards renewable energy sources—the macroeconomic consequences constitute an important factor in assessing the policy outcomes (Greening and Bataille 2009).

Just as bottom-up models have been trying to overcome their weaknesses by combining elements of top-down models, there have been many attempts by

Table 8 Overview of energy system models

Model	System coverage	Mathematical structure	Model perspective	Regions	Forecasting period
Calliope	Partial equilibrium	Optimisation	Bottom-up	National	
DNE21+	Limited macro feedback	Optimisation	Economic engineering	Regional (77)	2000–2100
EFOM	Partial equilibrium	Optimisation	Bottom-up	National	1974–2020
ERIS	Partial equilibrium	Optimisation	Bottom-up	Regional (12)	1990–2050
GENIE	Limited macro feedback	Optimisation	Bottom-up	Regional (4)	1995–2050
GET-LFL	Partial equilibrium	Optimisation	Bottom-up	Global	2000–2050
MARKAL/TIMES	Partial equilibrium	Optimisation	Bottom-up	Regional (5)	1990–2050
MEDEE 2	Partial equilibrium	Simulation	Bottom-up	National	1990–2040
MESSAGE	Partial equilibrium	Optimisation	Hybrid	Regional (11)	2005–2100
NEMS	Limited macro feedback	Market equilibrium	Economic engineering	National (USA)	2000–2030
POLES	Partial equilibrium	Market equilibrium	Economic engineering	Regional (18)	1980–2100
PRIMES	Partial equilibrium	Market equilibrium	Economic engineering	Regional (Europe)	2005–2050
WEM	Limited macro feedback	Optimisation	Hybrid	Regional (25)	2015–2040

top-down modellers to enhance their technological explicitness by incorporating elements of bottom-up models. Technological change has generally been captured in top-down models with the use of two key parameters: elasticity of substitution (ESUB) and the autonomous energy efficiency index (AEEI). ESUBs are used to capture the degree to which a relative price change will affect the substitution between any two pairs of aggregate inputs (capital, labour, energy, materials) and between different forms of final energy. In general, the easier it is to substitute capital for energy or one form of energy for another, the lower the cost of reducing energy use or GHG emissions. AEEI gives the rate at which price-independent technological evolution improves energy productivity, and itself depends on changes in technology and capital stock turnover. A higher AEEI means that the economy becomes energy-efficient faster. ESUB and AEEI are often estimated from aggregate, historical data, but these may not be good indicators for future values under different policy regimes. A policy focus on low to zero GHG emissions may have a substantial impact on AEEI and ESUB that is not captured by looking into the past. This inadequacy of top-down models partly explains the push towards greater

technological detail and making technological change endogenous. Another reason is that top-down models represent technological change as an abstract, aggregate phenomenon which may be adequate to assess economy-wide instruments like taxes and tradable permits but are unable to consider technology-focused policies. There are several different ways of incorporating elements of bottom-up models into top-down models, but there are limitations to how much technological detail can be incorporated without running into computational and other difficulties.

Technological change along with uncertainty treatment in the reviewed energy system models is presented in Table 9. It is evident that there exists a balance between endogenous and exogenous technological change among energy system models. Uncertainty treatment, however, is again treated mostly by means of deterministic approaches, i.e. scenario and sensitivity analysis, with the most prominent exception being that of the MARKAL/TIMES model, which also features Monte Carlo analysis according to Seebregts et al. (2002).

There exist a large number of general reviews of existing energy system models (e.g. Worrell et al. 2004; Jebaraj and Iniyar 2006), while Mundaca et al. (2010) provide a review of models with a specific focus on energy efficiency, also identifying a separate category of models called “accounting models”.

It should be noted that energy system models can be perceived as a cross-cutting category of models based on this classification, ranging from partial equilibrium to neoclassical/optimal growth models. In essence, they are partial equilibrium models, assuming equilibrium in one particular sector, i.e. the power sector. However, this category also includes models with features from other modelling approaches and structures, as shown in Table 8. For example, GET-LFL is an energy system model that can be classified as a cost minimisation IAM (Wei et al. 2015). The same applies for DNE21+, MIND and MESSAGE (Stanton et al. 2009). Furthermore, it should be mentioned that energy system models do not solely focus on the power sector but all economic sectors that are consumers of energy. For example, they are also used in studies oriented on the transport sector (e.g. Siskos et al. 2015). The latter is responsible for around 25% of energy-related GHG emissions today and is widely acknowledged to be the most inflexible sector of the energy system with regard to deep emissions reduction in the future (e.g. Hickman et al. 2010).

7 Macroeconometric Models

Environmental policy issues around 1990 pushed the development of computable general equilibrium models like the GREEN model of OECD, while in Europe, there was a parallel development of the CGE model GEM-E3 and the input-output econometric (or macroeconometric) model E3ME, which integrated energy and emissions in the economic model. E3ME stands for energy-environment-economy (E3) multisectoral model at the European level and, along with its variants, remains one of the most prominent macroeconometric models for appraisal of climate policy and climate-economy interactions. E3MG is a similar model that focuses on the

Table 9 Technological change and uncertainty treatment in energy system models

Model	Technological change		Uncertainty treatment		Uncertainty factors
	Endogenous	Exogenous	Deterministic	Stochastic	
DNE21+	✓	✓	Scenario analysis		Costs of emission reduction potential (Akimoto et al. 2010); policy in effect, carbon tax, stabilisation levels (Akinoto et al. 2004); energy demand (Yamaji et al. 2000)
EFOM		✓	Scenario analysis		Cost minimisation strategies (Van der Voort 1982); growth of electricity demand (Plinke et al. 1990)
ERIS	✓		Scenario analysis; sensitivity analysis	Subjective probability	Technological learning (Kyreos et al. 2000); depreciation rate (Barreto and Kypraios 2004)
GENIE	✓		Scenario analysis		Technological investment profiles, mitigation policy in effect (Mattsson and Wene 1997)
GET-LFL	✓		Scenario analysis		Emissions stabilisation levels, technological change (Hedenus et al. 2006)
MARKAL/TIMES	✓	✓	Scenario analysis; sensitivity analysis	Stochastic programming; Monte Carlo analysis (Seebregts et al. 2002)	Discount rate, fossil fuel prices, emission constraints (Seebregts et al. 2000); cost externalities (Rafaj and Kyreos 2007)
MEDEE 2		✓	Scenario analysis		Policy mix (Lapillonne 1980)
MESSAGE		✓	Scenario analysis; sensitivity analysis		Discount rate, operation time of wind turbines, overnight cost of nuclear power plants (Hainoun et al. 2010); electricity demand, GHG constraints (Sullivan et al. 2013)
NEMS		✓	Scenario analysis		Electric vehicle load profiles (Yu 2008)
POLES	✓		Scenario analysis		Climate change (Mima and Cricqui 2009); emission stabilisation (Kitous et al. 2010)
PRIMES		✓	Scenario analysis		CO ₂ emission reduction (Capros et al. 1999); scale of climate action, delay in climate action, technological diffusion delays (Capros et al. 2012)
WEM		✓	Scenario analysis		Policy mix (Kesicki and Yanagisawa 2015)

global level, as does the Oxford Global Macroeconomic and Energy Model, while the MDM-E3 model focuses on the UK economy (Table 10).

Macroeconometric models are “integrated” or hybrid in that they combine top-down macro models with bottom-up energy system models. The goal of integrating the two types of models is to provide a dynamic, non-linear picture of economic change in a detailed interindustry framework (West 2002). While static models can measure long-run comparative equilibrium solutions, the macroeconometric models are able to track the time path of the economy through

Table 10 Overview of macroeconometric models, including uncertainty treatment and technological change

Model	E3ME	E3MG	MDM-E3	Oxford global macroeconomic and energy model
Model perspective	Hybrid (Cambridge Econometrics 2014): top-down (energy); bottom-up (electricity supply)	Hybrid (Barker and Scriciecu 2010): top-down (interactions, feedback and spillover effects between the required investments and outcomes and the rest of the economy); bottom-up (energy technology model)	Hybrid (Barker et al. 2007): top-down; bottom-up (less detailed electricity sub-model, energy technology model)	Top-down
Regions	Global (59)	Global (20)	National	Global (22)
Forecasting period	1990–2100	1971–2100	Until 2030	2005–2020
Technological change	Endogenous	Endogenous	Exogenous	Exogenous
Uncertainty treatment	Deterministic (scenario analysis); stochastic (probabilistic analysis)	Deterministic (scenario analysis); stochastic (probabilistic analysis)	Deterministic (scenario analysis)	Deterministic (scenario analysis)
Uncertainty factors	All model parameters (Mercure et al. 2017); level of coordination in fiscal policies (Barker 1998, 1999)	Policy mix, carbon prices, new investments, emissions trading system structure (Barker et al. 2012); technology penetration levels (Dagoumas and Barker 2010)	Policy mix (Barker et al. 2007; Ekins and Etheridge 2006)	Policy mix, permit trading system structure (Cooper et al. 1999)

short-run disequilibrium adjustments. Macroeconometric models incorporate equations that trace the trajectory of national economic aggregates as well as related components of economic activity like labour, savings and consumption. These equations are estimated econometrically. Aggregate potential output is usually simulated as a function of aggregate inputs of capital and labour, and sometimes energy and materials. Transactions among economic sectors are described by input-output models. More or less aggregated sectoral demand functions are estimated by means of historical data, e.g. for energy services and food, allowing for projections of future trends in response to a carbon tax or other climate policies. The accuracy of these forecasts depends on the extent to which historical changes, e.g. technology changes induced by past price changes, are likely to be a good indicator for future changes.

Unlike CGE and optimal growth models, macroeconometric models do not assume that markets clear in the short and medium run, and demand and supply do not derive from optimising behaviour of consumers and producers. They are disequilibrium models with demand and supply approaching equilibrium in the long run. Because of the fact that they do not posit optimising behaviour on the part of agents or a “central planner”, they are characterised as simulation models, representing as closely as possible the dynamics of the real world. The economy and energy system are described by a set of rules that need not lead to full equilibrium. Some macroeconometric models also allow for structural unemployment resulting from inadequate demand for labour in the long run (Hourcade et al. 1996). CGE models usually assume that there is no unemployment or that the labour market clears. The Post-Keynesian E3ME macroeconometric model estimates labour with various disaggregated equations, e.g. working hours are estimated for men and women, different ages and sectors, thus allowing the model to forecast full-time and part-time workers. Disequilibrium in the labour market or unemployment is therefore a feature of this model. For this reason, it is sometimes argued that CGE models are more suitable for describing long-run steady-state behaviour, while macroeconometric models are more suitable for forecasting short-term outcomes. The parallel development of these “very different models” has given rise to an ongoing, often-heated discussion and conflicting positions between the input-output econometric and the CGE community (e.g. Grassini 2009). Robinson (2006) provides a nice account of the historical tension between CGE and macroeconometric models and the remaining theoretical difficulties of reconciling the approaches. Kratena and Streicher (2009) on the other hand attempt to better identify the key features differentiating the two approaches and suggest that the distance between them is much smaller than usually assumed.

One of the model outcomes that has often set the E3ME model apart from other top-down models is that it can give rise to negative costs, i.e. the imposition of climate policies can actually lead to increases in employment and output. Since structural unemployment is possible in this model, a transition to a low carbon economy can potentially enhance effective demand for labour reducing the lost output. In the E3MG model where the labour market and other markets may not clear, part of the impact of induced technological change arising from climate

policies is to raise growth through increased transfer of labour from traditional to modern sectors (Edenhofer et al. 2006).

As many CGE models assume the economy is always at an optimum, including full employment, any “constraints” resulting from climate policies can only result in additional costs to the economy. In general, first best models assume perfect markets and optimal policy implementation so that no-regret options are impossible. Second best models essentially allow for the possibility that climate policies can reduce market imperfections as a side benefit. This way, the costs of climate protection can be diminished or even become negative. Although imperfections or second best modelling is a fundamental feature of most macroeconomic models, since many of these draw heavily on the Keynesian tradition, different kinds of imperfections are often incorporated in GCE models and are usually implicitly assumed in most bottom-up (engineering) energy sector models (Sect. 6). Double dividends arise because climate policy redresses one imperfection (missing market or other institutions for climate protection) while also potentially reducing other market imperfections, e.g. barriers that prevent uptake of new technologies. When incorporating side benefits, for example, from reducing “distortionary” taxes with revenue from a carbon tax, in second best models, it would help to consider whether climate policies are the best way of dealing with many market imperfections and the extent to which these benefits should be attributed to climate policy per se.

8 Other Integrated Assessment Models

Optimal growth and CGE models are both based on a specific long-standing theoretical foundation so that most of these models can be understood as variations (though sometimes substantial) on a theme and comparability seems to be more straightforward. This section presents models that are hard to classify into any of the previously discussed models and delves into one well-known non-CGE model, the PAGE2002 model, as indicative of the kind of possible departures from standard neoclassical growth, CGE and macroeconomic models. These models are presented in Table 11. It should be noted that FUND should not be considered as a hybrid model, but it can run different optimisation modes, including top-down or bottom-up, cooperative or non-cooperative and with or without interregional capital transfer.

The PAGE2002 model attracted much attention recently due to it being the top-down model that the Stern team relied on for many of the much publicised aggregate climate change damages. One of the features that made it attractive to the Stern team was the model’s central focus on taking account of uncertainty in many of the climate-economy parameters. PAGE was developed as a computer simulation model in 1992 for use in decision-making within the European Commission. It was explicitly designed to be comprehensive but “accessible to policy makers” with the “simplest credible functional forms” (Hope et al. 1993), so that it remains transparent and able to run fast and repeatedly using a random sample of uncertain input

Table 11 Overview of models not falling into any of the previously discussed groups

Model	Model perspective	Regions	Forecasting period	Damages		Source
				Regions	Damage function	
CIAS	Top-down	Global (20)	2000–2100	Global	No damage treatment; holistic assessment of damages due to climate change	Schellnhuber et al. (2003)
FUND	Bottom-up and top-down	Global (16)	1950–2300	Global	Damage in FUND is distinguished between market and non-market effects; the former affect investment (economic growth) and consumption (welfare). The damage cost module per sector is presented in detail in (Ortiz and Markandya 2009), while other damage functions are used in the literature (Anthoff et al. 2009; Narita et al. 2009; Tol 2002)	Ortiz and Markandya (2009), Anthoff et al. (2009), Narita et al. (2009), Tol (2002)
ICAM-3	Bottom-up	Regional (11)	1975–2100	Regional	$D = a \cdot A + \gamma \cdot G + \lambda \cdot L(a, \gamma)$ α, β, γ comprise the policy choice, G is the vector of the costs of various geoengineering activities, L is the vector of losses (e.g. GDP), and λ the projection of the losses.	Dowlatabadi (1998)
IGSM2	Top-down	Global	2000–2100	Global	No damage treatment; IGSM2, along with the human systems component, comprise the MIT EPPA general equilibrium model	
IMAGE 2.4	Top-down	Global (26)	2000–2100	Global	$Y_t = A \cdot K_t^\alpha \cdot L_t^{1-\alpha}$ Y is GDP, K is capital, L is labor, α is elasticity of production, $Kt + 1 = Kt - \eta \cdot Kt + It$, η is depreciation, I is investment	Bouwman et al. (2006)
PAGE2002	Top-down	Regional (8)	2000–2200	Regional	$Dt = \frac{T_{\text{pret}}^{\text{pow}}}{2.5} \cdot W + (T_{\text{pret}} - T_{\text{dis}})P_{\text{dis}} \cdot W_{\text{dis}}$ Dt is damage as a percentage of GDP, T_{pre} is global temp above the pre-industrial age, T_{dis} is global temperature where is chance of discontinuity, P_{dis} is parameter positively related of a discontinuity, W is GDP lost for a 2.5° C warming	Hof et al. (2008)
PAGE09	Top-down	Regional (8)	2000–2200	Regional	$D = a \cdot \frac{T_{\text{act}}^\beta}{T_{\text{cal}}}$ where D is damage, a is damage at calibration temp, T_{cal} is calibration temp, T_{act} is actual temp rise, β is damage exponent	Pycroft et al. (2011)

parameters (Plambeck et al. 1997). A common criticism of IAMs is that they are so complex and opaque (“black box”) that it is hard to see how the various underlying assumptions affect their outcomes. The use of simple equations to capture complex climatic and economic phenomena is, according to Hope (2006), justified because the results approximate those of the most complex climate simulations and all aspects of climate change are subject to profound uncertainty. Uncertainty is a central focus of the model that builds up probability distributions of the results by representing the key inputs to the marginal impacts with probability distributions (stochastic treatment). An approximate probability distribution is generated for the model outputs of temperature rise, climate change damages and costs of adaptation and prevention. This is meant to help decision-makers perform a risk analysis so that they can select a policy that balances the cost of intervention against the benefits of mitigating potential climate change impacts (Plambeck et al. 1997).

A full description of the PAGE2002 model and all of its equations can be found in Hope (2006). A number of equations are focused on determining the temperature rise from excess concentrations of each of the greenhouse gases caused by human activities. There is no module of an economy. The economic side of the model is limited to a few equations that link market and non-market damages to temperature increases and calculate costs of avoiding or diminishing these damages through adaptation and/or emission reductions. In estimating damages arising from climate change, an “enumerative approach” is taken, which means that total damages are a simple aggregation of damages in individual sectors. There is thus no general equilibrium type of accounting for the many possible interactions between sectors. Although it has been assumed that this will lead to a lower estimate of total damages than that from a model that captures interactions, it is difficult to understand the magnitude of the difference. Climate change impacts are assumed to occur if temperature rises at a rate above some tolerable rate of change or level of temperature. These rates and levels vary with regions, and a regional multiplier captures these differences. Adaptation policies in any given year can increase both the tolerable rate of change and the level of temperature rise. The regional impact of climate change is therefore a function of the regional temperature rise and how much this is in excess of the regional tolerable rate of change or level of temperature that also depends on adaptation policies. A weighted index translates the regional temperature rise into monetary damage by multiplying the excess regional temperature rise by a regionally weighted percentage loss of GDP (based on estimates) times the regions’ estimated GDP. This is done for all eight regions in the model, for the market and non-market sectors and for every time period. By adding together market and non-market sector damages, the model finds aggregate damages per region per period, and this can then be discounted with regional and time variable discount rates. To get the net present value of global climate change impacts, the model aggregates the net present values of all regional damages.

Adaptation costs depend on the change in the rate and level of tolerable temperature rise that can be brought about by adaptation policy within each region. With appropriate weighting and use of uncertainty parameters, the net present value of costs can be estimated for different regional adaptation strategies. The costs of

preventing climate change are based on estimates of mitigating emissions below business as usual levels and are also weighted by region and discounted per time period. Only the direct costs of preventing greenhouse gas emissions are included in the model, although secondary benefits (like the concomitant reduction in atmospheric pollution) can be incorporated by reducing the preventative cost parameters. In many of the model's equations, parameters are used to capture uncertainty like that relating to the equilibrium warming from a doubling of CO₂ concentration, or the uncertainty about future growth or policy. In PAGE2002, there are about 80 uncertainty parameters depending on the regions and impact sectors used for a given run.

Although little can be obtained from a comparative analysis of models that fall into this "other models" class, Table 12 presents how uncertainty is treated and how technological change is introduced in these seven models.

A key difference between these models and models of other categories lies in the treatment of uncertain parameters. With the exception of the Community Integrated Assessment System (CIAS) model, all other models feature the capacity to approach uncertainty stochastically, by means of Monte Carlo analysis in FUND (Ackerman and Munitz 2012), IGSM2 (Webster et al. 2003, 2012) and IMAGE (Van Vuuren 2007) and probability distributions in ICAM-3 (e.g. Dowlatabadi 1998). PAGE, as already discussed, incorporates probability distributions for treating a large number of uncertain parameters, as well as Latin hypercube sampling, which was preferred over Monte Carlo analysis.

9 Concluding Remarks

This book chapter has tried to convey the broad outlines and main distinguishing features of alternative climate-economy model frameworks. The main objective has been to provide a simple overview and organising scheme into what can be a daunting wealth of different climate-economy or integrated assessment models. Rather than attempting to provide brief descriptions of a large sample of climate-economy models, the paper has tried to portray the main features of a small number of different classes of models, while delving into some key aspects of the models' perspective, structure, coverage and ways of treating uncertainty and technological advancement. Furthermore, no attempt was made to consider or compare results from alternative models; there are many surveys that compare model outcomes and consider how these differences can be explained either by the features of the model or by the specific assumptions embedded in these. Some suggest that the model framework can have substantial implications on the outcomes. Lanz and Rausch (2011) show systematic differences in outcomes from general equilibrium and energy system models. In contrast, one survey by Edenhofer et al. (2006) suggests that the underlying differences in outcomes lie not necessarily in the model type per se but the assumptions commonly made by the researchers working with different model types. The distinction between "model type" and "assumptions" may be

Table 12 Uncertainty and technological change in models not falling into any of the identified categories

Model	Technological change		Uncertainty treatment		Uncertainty factors
	Endogenous	Exogenous	Deterministic	Stochastic	
CIAS	✓		Scenario analysis (Warren et al. 2008)		Emission stabilisation levels (Warren et al. 2012)
FUND		✓	Scenario analysis	Monte Carlo analysis	Emission reduction gas mix (Tol 2006); climate damages (Ackerman and Munitz 2012)
ICAM-3	✓	✓	Scenario analysis; sensitivity analysis	Probability distributions	Mitigation action delay, experience with control technologies; more than 2000 stochastic parameters regarding paths followed, demographics, economic activity, resources and prices of fossil and non-fossil fuels, the energy intensity of economic activity, short-run budget adjustments when energy prices change and long-run lagged inter-fuel substitution elasticities (Dowlatabadi 1998)
IGSM2		✓	Scenario analysis	Monte Carlo analysis	Emission reduction gas mix, policy mix (Reilly et al. 2006); climate parameters, anthropogenic emissions (Webster et al. 2003), climate responses (Webster et al. 2012)
IMAGE 2.4		✓	Scenario analysis; sensitivity analysis	Monte Carlo analysis	Dietary variants; variations of CO ₂ fertilisation, recovery period of natural vegetation, potential feedbacks of decreasing demand on intensification in the agricultural system (Stehfest et al. 2009); large number of input parameters (Van Vuuren 2007)
PAGE2002	✓		Scenario analysis	Probability distributions; Latin hypercube sampling	Emission stabilisation levels (Hope 2008); more than 80 input parameters, depending on the number of sectors and regions selected (Hope 2006)
PAGE09	✓		Scenario analysis; sensitivity analysis	Probability distributions; Latin hypercube sampling	Emission stabilisation levels (Hope 2011); climate sensitivity, discount rate (Pycroft et al. 2011)

somewhat vague, but certainly a deeper understanding of climate-economy modelling really requires a detailed understanding of the role of the many assumptions explicitly or implicitly incorporated in these. Several climate-economy surveys do focus, *inter alia*, on just such a comparison of the role of assumptions (e.g. Stanton et al. 2009; Söderholm 2007).

It should be noted that many climate-economy models would not fall easily into any of the broad classifications presented here. Moreover, with the modellers' tendency to continuously develop and improve their models, there is much "cross-fertilisation" further blurring distinctions. The diversity of models has many sources. Model selection or design may be driven by different underlying research questions, like whether the focus is on calculating the cost of emission reductions or the long-term damages of climate change or whether one is comparing specific policies or trying to determine an overall optimal global climate policy target. If the focus is on understanding the impacts of climate change to a national economy, a more detailed multisectoral model may be more appropriate than a wealth maximising model that treats the economy as a single sector but captures the long-term global trajectory of the global economy. The differences may reflect deeper philosophical controversies, like whether it is meaningful to assume perfectly functioning markets when the object is to model climate change, which is the grandest instance of market failure extending to so many parts of the economy and with an unprecedented scale in time and space. This is why recent advancements or perspectives call for the use of modelling ensembles that highlight and make use of these differences in structure, design and theoretical foundations, in order to gain better insights (Doukas et al. 2018) and meaningfully inform policy processes; and, even such approaches may miss fundamental aspects that can only be explored with the help of stakeholders (Nikas et al. 2017). These differences may also result from the need to capture one particularly salient feature of climate change like uncertainty. The latter is associated with so many aspects of climate change and respective policy and is therefore, at least to some extent, being treated by means of deterministic or stochastic approaches embedded in the different modelling frameworks.

No doubt these and many other sources of model diversity will continue to drive the development of new and refinement of old models. Although this paper has barely scratched the surface of climate-economy modelling, the following quote seems like an apt closing for the great analytical challenges raised by our need to better understand the required policy response to climate change: "it is difficult to conceive an integrated model that will be able to provide the best answers to all questions. Instead, [...] the relative strengths and weaknesses of the different frameworks ensure that the combined contributions rather than individual models provide really valuable policy insights, to which new approaches and new frameworks for coupling economic and climate models can contribute" (Toth 2005).

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