Integrated Assessment Model of Climate Change: DICE/RICE Model

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Introduction

Environmental problems are intrinsically ones having strong roots in the natural sciences and require social and policy sciences to solve in an effective and efficient manner. E.g., Climate change involves a wide variety of sciences such as atmospheric chemistry and climate sciences, ecology, economics, political science, game theory, and international law.

Integrated assessment models (IAMs) can be defined as approaches that integrate knowledge from two or more domains into a single framework. These are sometimes theoretical but are increasingly computerized dynamic models of varying levels of complexity.

Outline

A review of the emerging problem of climate change.

A brief sketch of the rise of IAMs in the 1970s and beyond.

The DICE/RICE family of models, the purpose here is to provide readers an example of how such a model is developed and what the components are.

Major important open questions that continue to occupy IAM modelers. These involve issues such as the discount rate, uncertainty, the social cost of carbon, the potential for catastrophic climate change, and fat-tailed distributions.

Climate Change Problem

The atmospheric concentration of carbon dioxide of 390 parts per million (ppm) in 2011 far exceeds the range over the last 650,000 years, estimated to be between 180 and 300 ppm.

Current calculations from climate models are that doubling the amount of CO_2 or the equivalent in the atmosphere compared with pre-industrial levels will in equilibrium lead to an increase in the global surface temperature of 2 to 4.5 °C, with a best estimate of about 3 °C.

Other projected effects are increases in precipitation and evaporation, an increase in extreme events such as hurricanes, and a rise in sea levels of 0.2 to 0.6 meters over this century.

Some models also predict regional shifts, such as hotter and drier climates in mid-continental regions, including the U. S. Midwest.

Climate monitoring indicates that actual global warming is occurring in line with scientific predictions.

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UNFCCC: “The ultimate objective … is to achieve … stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system”

Kyoto Protocol

2 ^{0}C target

Climate change as a global public good

Economic modeling of climate change

Most economic studies of climate change, including most IAMs, integrate geophysical stocks and flows with economic stocks and flows. The major difference between IAMs and geophysical models is that economic measures include not only quantities but also valuations, which for market or near-market transactions are prices. The essence of an economic analysis is to convert or translate all economic activities into monetized values using a common unit of account, and then to compare different approaches by their impact on total values or a suite of values.

Both translation of different currencies into a common currency and conversion of values over time into a present value using a discount rate are deep issues in economics.

That is, economic welfare – properly measured – should include everything that is of value to people, even if those things are not included in the marketplace.

The central questions posed by economic approaches to climate change are the following: How sharply should countries reduce CO_2 and other GHG emissions? What should be the time profile of emissions reductions? How should the reductions be distributed across industries and countries?

There are also important and politically divisive issues about the instruments that should be used to impose cuts on consumers and businesses. Should there be a system of emissions limits imposed on firms, industries, and nations? Or should emissions reductions be primarily induced through taxes on GHGs? Should we subsidize green industries? What should be the relative contributions of rich and poor households or nations? Are regulations an effective substitute for fiscal instruments?

In practice, an economic analysis of climate change weighs the costs of slowing climate change against the damages of more rapid climate change.

Market signals, primarily higher prices on carbon fuels, to give signals and provide incentives for consumers and firms to change their energy use and reduce their carbon emissions. In the longer run, higher carbon prices will also provide incentives for firms to develop new technologies to ease the transition to a low-carbon future.

Those parts of the economy that are insulated from climate, such as air-conditioned houses and most manufacturing operations, will be little affected directly by climate change over the next century or so.

However, those human and natural systems that are "unmanaged," such as rain-fed agriculture, seasonal snow packs and river runoffs, and most natural ecosystems, may be significantly affected.

The economic damages from climate change with no interventions will be in the order of 2 to 3 percent of world output per year by the end of the 21st century, though large uncertainties are involved.

The damages are likely to be most heavily concentrated in low-income and tropical regions such as tropical Africa and India. While some countries may benefit from climate change.

Moreover, damage estimates cannot reliably include estimates of the costs of ecological impacts such as ocean acidification, species extinction, ecosystem disruption, or of the dangers posed by tipping points in the earth systems.

History of IAMs

Weyant et al. (1996) emphasized, as we will below, the importance of multiple approaches to development of IAMs because of the difficulty of encompassing all the important elements in a single model.

Kolstad (1998) writes that "nearly all the results have come from the so-called policy optimization models, the top-down economy-climate models. Virtually no new basic understanding appears to have emerged from the policy evaluation models…"

Uncertainty remains outside the models

Need for IAMs

The challenge of coping with global warming is particularly difficult because it spans many disciplines and parts of society.

This many-faceted nature also poses a challenge to natural and social scientists who must incorporate a wide variety of geophysical, economic, and political disciplines into their diagnoses and prescriptions.

The task of integrated modeling is to pull together the different aspects of a problem so that a decision or analysis can consider all important endogenous variables that operate simultaneously.

The point emphasized in IAMs is that we need to have *at a first level of approximation* models that operate all the modules simultaneously.

There is no linkage from the climate models to the economy and then back to emissions. It is exactly this linkage that is the purpose of integrating the different parts of the climate-change nexus in IAMs.

Earlier Energy Models

Several of the current integrated assessment models grew out of the energy models of the 1970s and 1980s.

T. Koopmans, A. Manne

The first integrated assessment models in climate change were basically energy models with an emissions model included, and later with other modules such as a carbon cycle and a small climate model.

The earliest versions of the DICE and RICE models in Nordhaus (1992, 1994) moved to a growth-theoretic framework similar to the Manne and Manne-Richels models.

Notable IAMs: PACE, IMAGE, MRN-NEEM, GTEM, MiniCAM, SGM, IGSM, WITCH, ADAGE, GEMINI, POLES, IGEM, MESSAGE, FUND, ETSAP-TIAM, MERGE, and DART

DICE/RICE Model

The DICE model is a globally aggregated model. The RICE-2010 model is essentially the same except that output and abatement have regional structures for 12 regions.

The DICE model views the economics of climate change from the perspective of neoclassical economic growth theory.

Economies make investments in capital, education, and technologies, thereby reducing consumption today, in order to increase consumption in the future.

The DICE model extends this approach by including the "natural capital" of the climate system as an additional kind of capital stock.

It views concentrations of GHGs as negative natural capital, and emissions reductions as investments that raise the quantity of natural capital.

By devoting output to emissions reductions, economies reduce consumption today but prevent economically harmful climate change and thereby increase consumption possibilities in the future.

Goals of IAMs

IAMs can be divided into two general classes – policy optimization and policy evaluation models (Weyant et al. 1996).

Policy evaluation models are generally recursive or equilibrium models that generate paths of important variables but do not optimize an economic outcome.

Policy optimization models have an objective function or welfare function that is maximized and can be used to evaluate alternative paths or policies.

The DICE/RICE models are primarily designed as policy optimization models

The objective function represents the goal implicit in the problem. For the DICE/RICE models, the objective function refers to the economic well-being (or utility) associated with a path of consumption.

The use of optimization can be interpreted in two ways: First, seen both, from a positive point of view, as a means of simulating the behavior of a system of competitive markets; and, from a normative point of view, as a possible approach to comparing the impact of alternative paths or policies on economic welfare.

In the DICE and RICE models, the world or individual regions are assumed to have well-defined preferences, represented by a social welfare function, which ranks different paths of consumption.

The social welfare function is increasing in the per capita consumption of each generation, with diminishing marginal utility of consumption.

The relative importance of different generations is affected by two central normative parameters, the pure rate of social time preference ("generational discounting") and the elasticity of the marginal utility of consumption (the "consumption elasticity" for short).

The DICE/RICE models assume that economic and climate policies should be designed to optimize the flow of consumption over time.

$$W = \sum_{t=1}^{Tmax} U[c(t), L(t)]R(t) \qquad (1)$$

where *W,* is the discounted sum of the populationweightedutility of per capita consumption, a social welfare function, *c* is per capita consumption, *L* ispopulation, and *R(t)* is the discount factor.

Assumption:

1.It involves a specific representation of the value or "utility" of consumption, represented by a constant elasticity utility function

$$U[c(t), L(t)] = L(t)[c(t)^{1-\alpha} / (1-\alpha)] \qquad (2)$$

This form assumes a constant elasticity of the marginal utility of consumption, α. If $\alpha$is close to zero, then the consumptions of different generations are close substitutes; if $\alpha$is high, then the consumptions are not close substitutes. Often, αwill also be used to represent risk aversion. A is calibratedin conjunction with the pure rate of time preference.

2. The value of consumption in a period is proportional to the population.

3. Social discount factor

$$R(t) = (1+\rho)^{-t} \tag{3}$$

R(t) is the discount factor, while the pure rate of social time preference, ρ , is the discount rate which provides the welfare weights on the utilities of different generations.

4. Baseline or no-controls case so represents the outcome of market and policy factors as they currently exist.

Economic Sectors

Assume a single commodity, which can be used for either consumption or investment. Consumption should be viewed broadly to include not only food and shelter but also non-market environmental amenities and services.

Population growth and technological change are region-specific and exogenous, while capital accumulation is determined by optimizing the flow of consumption over time for each region. Regional outputs and capital stocks are aggregated using purchasing power parity (PPP) exchange rates.

Population and the labour force are exogenous. These are simplified to be logistic-type equations. The growth of population in the first decade is given, and the growth rate declines so that total world population approaches a limit of 10.3 billion in 2100.

Output is produced with a Cobb-Douglas production function in capital, labor, and energy. Energy takes the form of either carbon-based fuels (such as coal) or non-carbon based technologies (such as solar or geothermal energy or nuclear power). Technological change takes two forms: economy-wide technological change and carbon-saving technological change. Carbon-saving technological change is modeled as reducing the ratio of CO_2 emissions to output. Carbon fuels are limited in supply. Substitution from carbon to non-carbon fuels takes place over time as carbon-based fuels become more expensive, either because of resource exhaustion or because policies are taken to limit carbon emissions.

Production is represented by a modification of a standard neoclassical production function. The underlying population and output estimates are aggregated up from a twelve-region model. Total output for each region is projected using a partial convergence model, and the outputs are then aggregated to the world total. The regional and global production functions are assumed to be constant-returns-to-scale Cobb-Douglas production functions in capital, labor, and Hicks-neutral technological change

[Note: Neutral technological change refers to the behaviour of technological change in models. A technological innovation is [Hicks neutral](), following John Hicks (1932), if a change in technology does not change the ratio of marginal product of capital to marginal product of labour for a given capital to labour ratio. A technological innovation is Harrod neutral (following Roy Harrod) if the technology is labour-augmenting (i.e., helps labor); it is Solow neutral if the technology is capital-augmenting (i.e., helps capital).]

Global output is shown as:

$$Q(t) = [1 - \Lambda(t)] A(t) K(t)^{\gamma} L(t)^{1-\gamma} \,/\, [1 + \Omega(t)] \tag{4}$$

In this specification, *Q(t)* is output net of damages and abatement, *A(t)* is total factor productivity, and *K(t)* is capital stock and services. The additional variables in the production function are $\Omega(t)$ and $\Lambda(t)$, which represent climate damages and abatement costs,

$$\Omega(t) - f_1[T_{AT}(t)] + f_2[SLR(t)] + f_3[M_{AT}(t)] \tag{5}$$

$$\Omega(t) = \psi_1 T_{AT}(t) + \psi_1 [T_{AT}(t)]^2 \tag{5'}$$

Equations (5) and (5') involve the economic impacts of climate change.

<u>The basic assumption is that the damages from gradual and small climate changes are modest, but that the damages rise non-linearly with the extent of climate change</u>. These estimates also assume that the damages are likely to be relatively larger for poor, small, and tropical countries than for rich, large and mid-latitude countries.

The functions (5) include damages from temperaturechange *(T_{AT})*, specific damages from sea-level rise *(SLR),* and the impacts of CO_2 fertilization, which are a function of atmospheric concentrations of CO_2 *(M_{AT}).*

To a first approximation, the damages are quadratic in temperature over the near term, and these are represented in equation (5').

Note also that the functional form in (4), which puts the damage ratio in the denominator, is designed to ensure that damages do not exceed 100% of output, and this limits the usefulness of this approach for catastrophic climate change. The damage function needs to be examined carefully or respecified in cases of higher warming or catastrophic damages.

$$\Lambda(t) = \Psi(t)\, \theta_1(t) \mu(t)^{\theta_2} \tag{6}$$

The abatement cost equation in (6) is a reduced-form type model in which the costs of emissions reductions are a function of the emissions reduction rate, *$\mu(t)$.* The abatement cost function assumes that abatement costs are proportional to output and to a polynomial function of the reduction rate. The cost function is estimated to be highly convex, indicating that the marginal cost of reductions rises from zero more than linearly with the reductions rate.

A new feature of the DICE-2007 and RICE-2010 models is that they explicitly include a backstop technology, which is a technology that can replace all fossil fuels[1] The backstop price is assumed to be initially high and to decline over time with carbon-saving technological change. In the full regional model, the backstop technology replaces 100 percent of carbon emissions at a cost of between \$230 and \$540 per ton of CO_2 depending upon the region in 2005 prices. The backstop technology is introduced into the model by setting the time path of the parameters in the abatement-cost equation (6) so that the marginal cost of abatement at a control rate of 100 percent is equal to the backstop price for each year.

The next three equations are standard accounting equations. Equation (7) states that output includes consumption plus gross investment. Equation (8) defines per capita consumption. Equation (9) states that the capital stock dynamics follows a perpetual inventory method with an exponential depreciation rate.

$$Q(t) = C(t) + I(t) \qquad (7)$$

$$c(t) = C(t) \,/\, L(t) \qquad (8)$$

$$K(t) = I(t) - \delta_K K(t-1) \qquad (9)$$

CO_2 emissions are projected as a function of total output, a time-varying emissions output ratio, and an emissions-control rate. The emissions-output ratio is estimated for individual regions and is then aggregated to the global ratio. The emissions-control rate is determined by the climate-change policy under examination. The cost of emissions reductions is parameterized by a log-linear function, which is calibrated to recent studies of the cost of emissions reductions.

The final two equations in the economic block are the emissions equation and the resource constraint on carbon fuels. Uncontrolled industrial CO2 emissions in Equation (10) are given by a level of carbon intensity, $\sigma(t)$, times output. Actual emissions are then reduced by one minus the emissions-reduction rate, $\mu(t)$, described above. The carbon intensity is taken to be exogenous and is built up from emissions estimates of the twelve regions, whereas the emissions-reduction rate is the control variable in the different experiments.

$$E_{Ind}(t) = \sigma(t)[1 - \mu(t)]A(t)\,K(t)^{\gamma}\,L(t)^{1-\gamma} \qquad (10)$$

[1]**Backstop resources** theory states that as a heavily used limited resource becomes expensive, alternative resources will become cheap by comparison, therefore making the alternatives economically viable options. In the long term, the theory implies faith that technological progress will allow backstop resources to be essentially unlimited: http://en.wikipedia.org/wiki/Backstop_resources

$$CCum \geq \sum_{t=1}^{Tmax} E_{Ind}(t) \tag{11}$$

Equation (11) is a limitation on total resources of carbon fuels, given by *CCum.*The model assumes that incremental extraction costs are zero and that carbon fuels are efficiently allocated over time by the market, producing the optimal Hotelling rents on carbon fuels.

Geophysical Sectors

The major differentiating feature of the DICE/RICE models is the inclusion of several geophysical relationships that link the economy with the different forces affecting climate change. These relationships include the carbon cycle, a radiative forcing equation, climate change equations, and a climate-damage relationship. A key feature of IAMs is that the modules operate in an integrated fashion rather than taking inputs as exogenous inputs from other models or assumptions. The next equations (12) to (18) link economic activity and greenhouse-gas emissions to the carbon cycle, radiativeforcings, and climate change.

In the DICE/RICE-2010 models, the only GHG that is subject to controls is industrial CO_2. This reflects the fact that CO_2 is the major contributor to global warming and that other GHGs are likely to be controlled in different ways. Other GHGs are included as exogenous trends in radiative forcing; these include primarily CO_2 emissions from land-use changes, other well-mixed GHGs, and aerosols.

Recall that equation (10) generated industrial emissions of CO_2. Equation (12) then generates total CO_2 emissions as the sum of industrial and land-use emissions. CO_2 arising from land-use changes are exogenous and are projected based on studies by other modeling groups.

$$E(t) = E_{Ind}(t) + E_{Land}(t) \tag{12}$$

The carbon cycle is based upon a three-reservoir model calibrated to existing carbon cycle models and historical data. We assume that there are three reservoirs for carbon. The variables $M_{AT}(t)$, $M_{UP}(t)$, and $M_{LO}(t)$ represent carbon in the atmosphere, carbon in a quickly mixing reservoir in the upper oceans and the biosphere, and carbon in the deep oceans. Carbon flows in both directions between adjacent reservoirs. The mixing between the deep oceans and other reservoirs is extremely slow. The deep oceans provide a finite, albeit vast, sink for carbon in the long run. Each of the three reservoirs is assumed to be well-mixed in the short run. Equations (13) through (15) represent the equations of the carbon cycle.

$$M_{AT}(t) = E(t) + \phi_{11} M_{AT}(t-1) + \phi_{21} M_{UP}(t-1) \tag{13}$$

$$M_{UP}(t) = \phi_{12} M_{AT}(t-1) + \phi_{22} M_{UP}(t-1) + \phi_{32} M_{LO}(t-1) \tag{14}$$

$$M_{LO}(t) = \phi_{23} M_{UP}(t-1) + \phi_{33} M_{LO}(t-1) \tag{15}$$

The parameters φ_{ij}represent the flow parameters of the carbon (between carbon reservoirs). Note that emissions flow into the atmosphere.

The next step concerns the relationship between the accumulation of GHGs and climate change. The climate equations are a simplified representation that includes an equation for radiative forcing and two equations for the climate system. The radiative forcing equation calculates the impact of the accumulation of GHGs on the radiation balance of the globe. The climate equations calculate the mean surface temperature of the globe and the average temperature of the deep oceans for each time-step. These equations draw upon and are calibrated with large-scale general circulation models of the atmosphere and ocean systems.

Accumulations of GHGs lead to warming at the earth's surface through increases in radiative forcing. The relationship between GHG accumulations and increased radiative forcing is derived from empirical measurements and climate models

$$F(t) = \eta\{log_2[M_{AT}(t) / M_{AT}(1750)]\} + F_{EX}(t) \qquad (16)$$

F(t) is the change in total radiativeforcings of greenhouse gases since 1750 from anthropogenic sources such as CO_2, $F_{EX}(t)$ is exogenous forcings, and the first term is the forcings due to CO_2.

Higher radiative forcing warms the atmospheric layer, which then warms the upper ocean, gradually warming the deep ocean. The lags in the system are primarily due to the diffusive inertia of the different layers. The latest version of the models adjusted the climate sensitivity to the center of the IPCC range of 3.2 °C for an equilibrium CO2 doubling. The dynamics are determined so that the transient temperature sensitivity is the same as the average of the AOGCMs reviewed in IPCC Fourth Assessment Report 2007.

$$T_{AT}(t) = T_{AT}(t-1) + \xi_1\{F(t) \quad \xi_2 T_{AT}(t-1) \quad \xi_3[T_{AT}(t-1) \quad T_{LO}(t-1)]\} \qquad (17)$$

$$T_{LO}(t) = T_{LO}(t-1) + \xi_4\{T_{AT}(t-1) - T_{LO}(t-1)]\} \qquad (18)$$

$T_{AT}(t)$ and $T_{LO}(t)$ represent respectively the mean surface temperature and the temperature of the deep oceans. Note that the equilibrium temperature sensitivity is given by

$$\Delta T_{AT} = \Delta F(t) / \xi_2 \qquad (19)$$

This completes the description of the DICE model.

RICE Model:

$$W = \sum_{t=1}^{Tmax} \sum_{I=1}^{N} \psi_{I,t} U^I[c^I(t), L^I(t)]R^I(t)$$

Where t denotes time and I denotes regions (there are 12 regions in the RICE model). See also Nodhaus PNAS (2010) paper for details.

Applications of the IAMs

Integrated assessment models are useful devices to improve our understanding of tradeoffs, costs, benefits, and uncertainties. They are not truth machines, although they sometimes can be helpful in rooting out obvious inconsistencies and errors.

Making consistent projections

Calculating the impacts of alternative assumptions on important variables such as output, emissions, temperature change, and impacts.

Tracing through the effects of alternative policies on all variables in a consistent manner, as well as estimating the costs and benefits of alternative strategies.

Estimating the uncertainties associated with alternative variables and strategies.

Calculating the effects of reducing uncertainties about key parameters or variables, as well as estimating the value of research and new technologies.

Policy Scenarios

One advantage of IAMs is that they can compare the economic and climate trajectories associated with different policy approaches.

Baseline: No climate-change policies are adopted.

Optimal: Climate-change policies maximize economic welfare, with full participation by all nations starting in 2010 and without climatic constraints.

Temperature-limited: The optimal policies are undertaken subject to a further constraint that global temperature does not exceed 2 °C above the 1900 average.

Copenhagen Accord: High-income countries implement deep emissions reductions similar to those included in the current U.S. proposals, with developing countries following in the next 2-5 decades. It is assumed that implementation is through system of national emission caps with full emissions trading within and among countries (although a harmonized carbon tax would lead to the same results).

Copenhagen Accord with only rich countries: High-income countries implement deep reductions as in last scenario, but developing countries do not participate until the 22^{nd} C.

Major Results

Figure 5 shows global CO_2 emissions under each of the 5 policy scenarios.

Atmospheric concentrations of CO_2 see Figure 6 and Table 4

Global temperature projections, shown in Figure 7 and Table 4,
The most important outputs of integrated economic models of climate change are the near-term "carbon prices." (Table 5, 6, 7, Figure 8)

Table 8 shows the large stakes involved in climate-change policies as measured by aggregate costs and benefits.Using the model discount rates, the optimal scenario raises the present value of world income by $9.1 trillion, or 0.35% of discounted income. This is equivalent to an annuity of $454 billion per year at a 5% annual discount rate. Imposing the 2 °C temperature constraint has a significant economic penalty, reducing the net benefit by almost half, because of the difficulty of attaining that target with so much inertia in the climate system. The Copenhagen Accord with phased-in participation of developing countries has substantial net benefits, but lack of participation in the "rich only" case reduces these substantially.

Figure 9 and Table 9 shows the path of net costs as a percent of income for 7 major regions. Costs rise gradually over the coming decades and reach around 1% of national income for the high-income countries in the mid-21st century.

Some Major Issues for Research in Integrated Assessment Modeling

The social cost of carbon: This concept represents the economic cost caused by an additional ton of carbon dioxide emissions (or more succinctly carbon) or its equivalent. In a more precise definition, it is the change in the discounted value of the utility of consumption denominated in terms of current consumption per unit of additional emissions. In the language of mathematical programming, the SCC is the shadow price of carbon emissions along a reference path of output, emissions, and climate change. For example, the US government has undertaken rulemaking proceedings to determine the SCC for use in such areas as subsidies for the installation of low carbon energy sources, regulations requiring energy efficiency standards in buildings and motor vehicles, and rebates for home insulation materials.

Complexity and transparency

Positive versus normative models

The discount rate, *discount rate on goods, generational discount rate (pure time preference rate)*
The major point to recognize is that the economic units in the economy are generations or cohorts. Similarly, the key parameters are α (the elasticity of utility with respect to a generation's consumption, or consumption elasticity) and ρ (the generational discount rate). Optimizing the social welfare function with a constant population, no risk or taxes, and a constant rate of growth of consumption across different generation, g^*, yields the standard equation for the relationship between the equilibrium real return on capital, r^*, and the other parameters, $r^* = \rho + \alpha g^*$. This is usually called the Ramsey equation.

Uncertainty for thin-tailed distributions

Higher-moment uncertainty ("fat tails") and catastrophic climate change

Strategic considerations and the game-theoretic aspects of climate-change policy

Modeling Technological Change: induced innovation

There have been two approaches to including induced innovation – the research model and the learning model.

Work with the DICE model (Nordhaus 2002), the ENTICE model (Popp 2004) and the WITCH model (Bosetti et al. 2009) have developed the research-model approach in the context of climate change. One of the major findings is that the omission of endogenous technological change has a major impact on welfare but has only a small effect on the temperature path or on the path of the optimal carbon price (Popp 2004).

Perhaps the single most important set of results from IAMs has been the concepts and estimation of efficient paths of abatement and carbon pricing required for slowing climate change. There was essentially no awareness of the importance of carbon pricing two decades ago, and few would have hazarded an estimate of the appropriate carbon price. Today, in part because of developments in IAMs, carbon prices and estimates of the social cost of carbon are actually integrated into the regulatory decisions of major countries.